

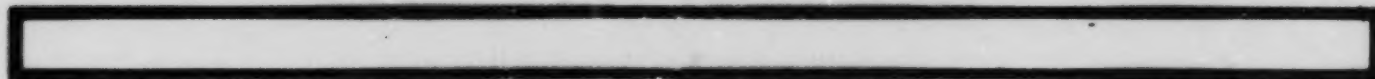
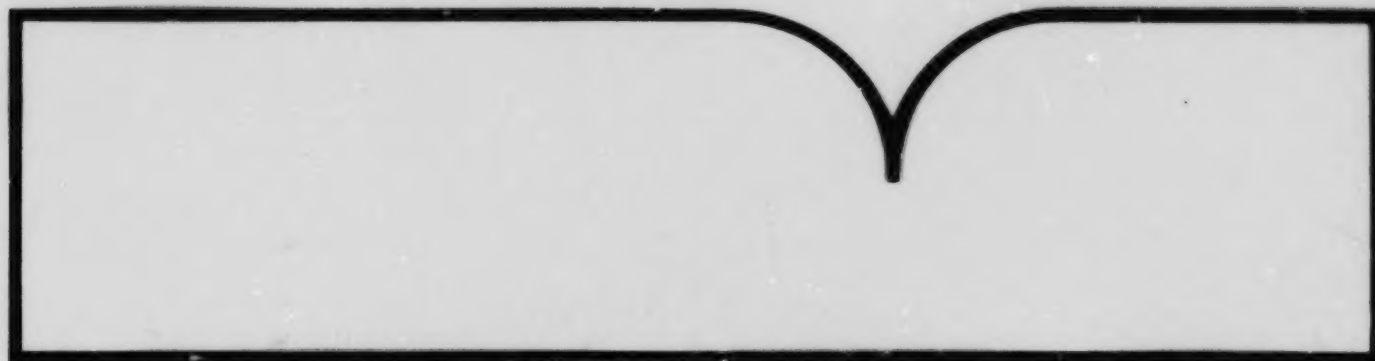
Application of Municipal
Sludges on Energy Crops
A Feasibility Analysis

InterTechnology/Solar Corp., Warrenton, VA

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

Sep 83



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TECHNICAL REPORT DATA (Please read instructions on the reverse before completing)		
1. REPORT NO. EPA-600/2-83-095	2.	3. RECIPIENT'S ACCESSION NO. PB8 4 101559
4. TITLE AND SUBTITLE APPLICATION OF MUNICIPAL SLUDGES ON ENERGY CROPS: A FEASIBILITY ANALYSIS	5. REPORT DATE September 1983	
	6. PERFORMING ORGANIZATION CODE	
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Intertechnology/Solar Corporation Warrenton, Virginia 22186	10. PROGRAM ELEMENT NO.	
	11. CONTRACT/GRANT NO. Contract 68-01-4688	
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268	13. TYPE OF REPORT AND PERIOD COVERED Final	
	14. SPONSORING AGENCY CODE EPA/600/14	
15. SUPPLEMENTARY NOTES Project Officer: Donald J. Ehreth		
16. ABSTRACT This study evaluates the feasibility of disposing of treated municipal sludge on marginal land used to grow energy crops. In contrast to the use of sludge on agricultural crops, its use on energy crops avoids most of the problems associated with the presence of heavy metals and other pollutants in sludge. This analysis shows that replacing sludge incineration and /or landfilling with land spreading on energy crops can result in dollar and energy credits to municipalities implementing this alternative. The potential economic advantage of the energy crop approach is, however, very sensitive to local factors such as the value of the credits gained from eliminating incineration or landfilling and the annual yields of the energy crops. Energy crop production may not result in a net revenue for a city, since the costs of spreading the sludge and processing the energy crop will be greater than the dollar value of the crop itself. And because the present market value of farm products is greater than that of energy crops, disposal of sludge on energy crops is slightly more costly than its disposal on agricultural crops. But the energy crop approach does result in the generation of clean, renewable energy, whereas the agricultural crop approach is an energy-consuming process. The analysis presented here is valid for cities with populations of 50,000 to several million, and it applies essentially to all regions of the United States.		
17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS (This Report) UNCLASSIFIED	21. NO. OF PAGES 175
	20. SECURITY CLASS (This page) UNCLASSIFIED	22. PRICE

PB84-101559

EPA-600/2-83-095
September 1983

APPLICATION OF MUNICIPAL SLUDGES ON ENERGY CROPS:
A FEASIBILITY ANALYSIS

by

InterTechnology/Solar Corporation
Warrenton, Virginia 22186

Contract No. 68-01-4688

Project Officer

Donald J. Ehreth
Waste Management Division
Office of Research and Development
Washington, D. C. 20460

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OFFICE OF RESEARCH AND DEVELOPMENT
U. S. ENVIRONMENTAL PROTECTION AGENCY
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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

Contributing to the solution of three societal problems with one activity is an attractive possibility. This report assesses the feasibility of using a municipal waste (sewage sludge) to ameliorate a soil problem (low productivity) and to produce crops that help supply the energy needs of the country.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

This study evaluates the feasibility of disposing of treated municipal sludge on marginal land used to grow energy crops. In contrast to the use of sludge on agricultural crops, its use on energy crops avoids most of the problems associated with the presence of heavy metals and other pollutants in sludge. This analysis shows that replacing sludge incineration and/or landfilling with land spreading on energy crops can result in dollar and energy credits to municipalities implementing this alternative. The potential economic advantage of the energy crop approach is, however, very sensitive to local factors such as the value of the credits gained from eliminating incineration or landfilling and the annual yields of the energy crops. Energy crop production may not result in a net revenue for a city, since the costs of spreading the sludge and processing the energy crop will be greater than the dollar value of the crop itself. And because the present market value of farm products is greater than that of energy crops, disposal of sludge on energy crops is slightly more costly than its disposal on agricultural crops. But the energy crop approach does result in the generation of clean, renewable energy, whereas the agricultural crop approach is an energy-consuming process. The analysis presented here is valid for cities with populations of 50,000 to several million, and it applies essentially to all regions of the United States.

This report was submitted in fulfillment of Contract No. 68-01-4688 by InterTechnology Solar Corporation under the sponsorship of the U.S. Environmental Protection Agency.

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ACKNOWLEDGMENTS

The following individuals at InterTechnology/Solar Corporation have contributed to the present report: Dr. L. A. Alexander, Mr. C. H. Harmer, Mr. J. W. Meredith, Dr. W. B. Scholten, and Mr. C. W. Vail. Their cooperation and diligence is gratefully acknowledged. Our appreciation also goes to Dr. F. A. Costello for his support and interest in this project.

We also wish to thank Mr. G. K. Dotson, U.S. Environmental Protection Agency, Dr. R. J. Lofy, SCS Engineers; Dr. L. E. Sommers, Purdue University; and Dr. W. E. Sopper, Pennsylvania State University for making data available to us and discussing various aspects of this study.

Acknowledgments are also due to Mrs. B. E. Choate, Mrs. C. M. Harris, Mrs. M. Helsing, Mrs. G. S. Marshall, Miss C. Stanley, and Mrs. D. Thompson for their contributions to the preparation of this report.

Finally, our appreciation goes to Mr. Donald J. Ehreth of the U.S. Environmental Protection Agency, Waste Management Division, for his constant support, interest, and help during the course of this study.

Jean Francois Henry
Project Manager

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SECTION 1

INTRODUCTION

OBJECTIVES AND APPROACH

This study examines the use of sewage sludge for energy crop production, an activity that has the potential for solving three societal problems at once: Municipal waste (sewage sludge) is disposed of by using it to ameliorate a soil problem (low productivity) and to produce crops that help supply the energy needs of the country. The objectives of the project were as follows:

1. To assess the economic feasibility of using municipal sludge on land devoted to the production of energy crops;
2. To determine the net energy balance resulting from the generation of energy crops from sludge; and
3. To assess the potential impact of this sludge disposal method on a national scale.

The term energy crop refers to any form of biomass (agricultural, woody, or grass crops) grown specifically for its energy value. This energy value may be recovered by direct combustion or through conversion to another form of energy.

Application of municipal sludge to agricultural land or recreational areas is recognized as one of the promising methods for ultimate sludge disposal. Applications of these residues to food crops, however, might create serious problems when the crops become part of the food chain. Disposal on recreational areas also requires caution because of the presence of pathogens.

The approach explored in this study is to apply the urban sludge to land, especially marginal land, and to generate energy crops or crops produced exclusively for their fuel value. This approach would thus essentially eliminate the risk of human or animal contamination by heavy metals and other pollutants, and it would also generate a renewable source of energy that would reduce the dependence of the local economy on outside energy sources.

SUMMARY

The study considers the situation expected in 1985, when most municipalities will have included some form of secondary treatment and sludge management for their wastewater treatment plants. Sludge disposal on

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energy-crop-producing land is compared from the point of view of finances and energy balance with three other methods of stabilized sludge disposal--incineration, landfilling, and application to agricultural crops. The comparison is made for cities with populations of 10,000 to 4 million.

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Four classes of energy crops were considered: (1) Fast-growing, short-rotation hardwood plantations, (2) arid region or desert shrubs, (3) sugar crops, and (4) grain crops. In the first two cases, wood chips for fuel or electricity would be the final products generated from the energy crop, whereas in the latter two, ethanol is assumed to be produced from the crops.

The economic evaluation of the energy crop from sludge concept includes the following items: (1) the credits to the municipality resulting from the elimination (substitution) of the standard methods of sludge disposal (i.e., incineration or landfilling) and from the sales of the energy crop or its energy product, (2) the costs incurred in transporting the sludge to the plantation, (3) the costs of storing the sludge if needed, (4) the expense of generating and harvesting the energy crop, (5) the price of leasing or buying the necessary crop land, and (6) the costs incurred in transporting the energy crop or its product to its point of use. The same credits and debits are applicable for the disposal of sludge on agricultural crops. No credit was taken for improvement of the land as a result of sludge application.

The energy balance evaluation takes into account the energy credits resulting from the elimination of incineration or landfilling and from the generation of the energy crop. Also considered is the energy consumption associated with the transportation of the sludge and the energy crop, and with the production and conversion of the energy crop. The same energy credits and debits apply for agricultural crops, except for the credit associated with the energy value of the energy crop.

The analysis is performed for five climatic regions encompassing the continental United States. Particular emphasis was placed on fast-growing hardwood crops, since in the course of the study, these crops appeared to offer the most flexibility and the widest range of applicability.

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SECTION 2

CONCLUSIONS

ECONOMIC COMPARISONS

Sludge Disposal on Energy Crops Versus Incineration or Landfilling

1. For all regions of the United States, the cost of sludge disposal (annual operation and maintenance costs) through woody energy crops is significantly lower (in most cases about 50%) than that of disposal through landfilling or incineration.

A sensitivity analysis shows, however, that this economic advantage of the energy crop approach is extremely sensitive to the value of the credits resulting from the elimination of incineration or landfilling, to the biomass yields, and to the local market value of electricity when the latter is the end-product of the energy crop. Specifically, variations of credits, yields, and price of electricity within a range of values that can be expected in practice may eliminate completely the economic advantage of the energy crop approach over incineration or landfilling. Variations that can be expected in the cost of biomass production or in the transportation distance of the sludge to the plantation do have a minor effect on the economic advantage of the energy crop approach, but variations in all of the above factors have negligible effects on this favorable energy balance.

2. For cities with populations of 2 million or more, the production of electricity from the biomass rather than the use of wood chips as fuel for process heat or other uses is an economic alternative for regions where fossil fuels delivered to the electric power plants cost more than about \$1.00 per million Btu. This is the case everywhere in the United States when natural gas, oil, or nuclear fuel are the primary sources of energy and in many regions of the country when low-sulfur coal is the source of energy for electricity production.
3. Ethanol production from sludge-grown sugar crops is not economical for population centers smaller than about 5 million if all the raw material for the ethanol conversion plant is supplied by the energy crop plantation.

4. Ethanol production from sludge-grown grain crops is not economical for population centers smaller than about 50 million if all the raw material for the conversion plant is supplied by the energy crop plantation.

Sludge Disposal on Energy Crops Versus Agricultural Crops

1. For all regions, the production costs of energy crops and of agricultural crops generated from the disposal of the same amount of sludge are comparable. This result is expected because the sludge handling and field operations are similar in both cases.
2. After credit is taken for crop sales generated in either case, the cost of sludge disposal on agricultural crops is generally lower than for disposal through the generation of energy crops.
3. In view of the large seasonal and annual fluctuations in the prices paid to farmers for agricultural products, the economic advantage of agricultural crops over energy crops could vary widely and unpredictably in the years to come. In contrast, the price of biomass sold for its fuel value will follow the upward cost trend displayed by fossil fuels (3% above general inflation for coal, and more for other fuels). The credit for the sale of biomass fuel is thus expected to maintain or increase its value expressed in 1977 dollars. The present economic advantage of agricultural crops over energy crops could thus be significantly reduced or even eliminated by 1985.

CAPITAL INVESTMENT COMPARISONS

Sludge Disposal on Energy Crops Versus Incineration or Landfilling

1. The capital investment required to dispose of sludge through the energy crop approach is larger than the capital cost of incinerators for centers with populations larger than about 200,000. The difference in investment is mostly due to the sludge transportation equipment (pipeline). If electricity or ethanol is the final product of the sludge disposal operation, the capital investment required is much larger than for incineration. This study is based on replacing an existing sludge management plan (incineration, landfilling, and application to agricultural lands) with the energy crop concept rather than a comparison of options for a city that has no sludge management plan.

For cities with populations of 50,000 to about 200,000, the capital investment for the energy crop method of sludge disposal is significantly lower than for incineration.

The major capital investment items required for sludge disposal through landfilling are land purchase and sludge transportation equipment. These costs will be comparable to those incurred for the same items for the energy crop approach, but they will probably be higher if landfilling occurs in the vicinity of the city considered.

2. Between the two most attractive energy crop approaches (i.e., woody fuel and electricity from woody fuel), the required investment strongly favors the production of woody fuel.

Sludge Disposal on Energy Crops Versus Agricultural Crops

The capital investments required for sludge disposal on energy or agricultural crops are comparable.

ENERGY BALANCE COMPARISONS

Sludge Disposal on Energy Crops Versus Incineration or Landfilling

1. When incineration is replaced by disposal through woody energy crops, an overall energy credit occurs of 37 to 42 Giga Joules (GJ)/dry metric ton of sludge treated (32 to 36×10^6 Btu/dry ton). This credit is a result of a reduction of fossil fuel consumption of 3.6 to 8.6 GJ/dry metric ton of sludge (3.1 to 7.4×10^6 Btu/dry ton) and the generation of about 33 GJ/dry metric ton of sludge (28×10^6 Btu/dry ton) of clean biomass fuel.
2. When disposal by landfilling is replaced by disposal through woody energy crops, an overall energy credit occurs of about 34 GJ/dry metric ton of sludge (30×10^6 Btu/dry ton). This credit results from a reduction of fossil fuel consumption of about 1.3 GJ/dry metric ton of sludge (1.1×10^6 Btu/dry ton) and the generation of about 33 GJ/dry metric ton of sludge (28.6×10^6 Btu/dry ton) of clean biomass fuel.
3. When the biomass is used to produce electricity rather than being used directly as fuel for process heat or other applications, the overall energy balance is still in favor of the energy-crop-to-electricity approach.
4. The production of ethanol from sugar crops or from grain crops also results in a net energy credit. But this alternative is not attractive in view of the large population centers required to support the ethanol production plant.

Sludge Disposal on Energy Crops Versus Agricultural Crops

1. Disposal of sludge on energy crops generates about 33 GJ/dry metric ton of sludge treated (28.6×10^6 Btu/dry ton) of clean biomass fuel, whereas disposal on agricultural crops produces none.

2. As was the case for energy crops, disposal of sludge on agricultural crops reduces fossil fuel consumption by 3.6 to 8.6 GJ/dry metric ton of sludge treated (3.1 to 7.4×10^6 Btu/dry ton) and by 1.3 GJ/dry metric ton of sludge treated (1.1×10^6 Btu/dry ton) when compared with disposal by incineration and landfilling, respectively.

POTENTIAL IMPACT

In view of the extreme sensitivity to local factors shown by the results of the economic analysis, it is meaningless at this point to attempt an evaluation of the potential impact on a national scale of sludge disposal through energy crops.

LAND REQUIREMENTS

The land requirements for implementing disposal of sludge through energy crops are minimal. If incineration or landfilling were replaced by land disposal on energy crops on a national basis, the total land area required would only be about 240,000 ha (about 600,000 acres), a land area equivalent to only about 2% of all the commercial timberland presently owned by States, counties, and municipalities. In the energy-crop approach, marginal land is proposed for sludge disposal and energy crop growth. Thus sludge disposal through energy crops would not encroach on land areas presently used or reserved for farming.

ENVIRONMENTAL AND SOCIAL ASPECTS

The disposal of sludge through the growth of energy crops is attractive from an environmental point of view: It generates perpetually renewable energy of low sulfur content, and it does not affect the carbon dioxide balance in the atmosphere. Also, this method of disposal significantly reduces the problems associated with the presence of heavy metals in the sludge. Sludge disposal on energy crops is a source of permanent employment, particularly in the rural areas where the energy crop plantations are operated. A detailed balance between the number of jobs lost through elimination of incineration or landfilling and the number of jobs created through the energy crop plantation has not been performed, however. Finally, sludge disposal will upgrade the quality of the land used to grow energy crops. If land-use regulations permit, this upgraded marginal land could be brought back to farming if needed.

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RECOMMENDATIONS

The conclusions derived from this study indicate that disposing of municipal sludge through energy crops is feasible in many cases from the standpoints of economics, energy balance, and environmental concerns. Thus we strongly recommend that this approach be further investigated along the following lines:

1. Case studies should be done of a small, a medium, and a large city. Each of these cases presents specific problems. Small cities display the largest uncertainties in cost of disposal. Medium cities give the option of several methods of transportation of sludge. And large cities raise the important problem of transportation distance in relation to land value. Specific case studies that take into account local factors, institutional problems, and regulations will refine some aspects of the present study as well as generate the conceptual design background needed for eventual demonstrations.
2. The Energy PlantationTM model used in the analysis should be revised to integrate the sludge disposal operation needed when energy crops from sludge are grown. In the present study, these modifications to the model were made manually. Establishment of a general computer model for the analysis and design of energy crop plantations would be most useful in the future.
3. One of the uncertainties of the study deals with the productivity of desert or arid land species grown under managed conditions with addition of sludge. This topic should first be investigated on the basis of available data; then, if warranted, an experimental program should be initiated. Data needed include a survey of species adapted to the climatic conditions, heating values, potential environmental effects of energy crop plantations on the biome, and productivities under various levels and conditions of management, water, and nutrient balances.
4. Although some data have already been generated on the response of hardwoods and softwoods to effluent and sludge applications, further data should be gathered, particularly concerning the influence of heavy metals on growth and coppice (second growth) behavior of hardwoods subjected to sludge applications.

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5. The integration of energy crops grown from municipal sludge as auxiliary fuel into solid waste disposal operations should be investigated.

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DISCUSSION

STUDY OBJECTIVES

The objectives of this study are (1) to assess the feasibility of using municipal sludge on land devoted to the production of energy crops as a method of sludge disposal, (2) to determine the energy balance resulting from the generation of energy crops from sludge, and (3) to assess the potential impact of this method of sludge disposal on a national scale. The term "energy crop" refers to any form of biomass (agricultural, woody, or grass crops) grown specifically for its energy value. This energy value may be recovered by direct combustion or through conversion to another form of energy.

Land application is one of the most promising approaches to the disposal of municipal sludge. Application of these residues to food crops or public or private recreation areas (parks, golf courses) has been demonstrated to be workable. In the first case, however, potential problems may occur when the crops become part of the food chain: A fraction of the heavy metals and other contaminants present in the sludge are assimilated by the growing food crop, restrict the usefulness of these crops as food, and therefore impose limitations on the rates of application (and thus of disposal) of the sludge. In the second case, caution must still be exercised because of the presence of pathogens. The benefit of land application here is limited to the irrigation and fertilizer value of the sludge.

The approach explored in this study is to apply the sludge to land that produces energy crops, thus eliminating the restrictions on usage of the crops resulting from the presence of pollutants. Also, if the site conditions permit, the sludge application rate can be increased, as the product of the land does not enter the food chain. The sludge application rate is a site-specific factor that must be evaluated on a case-by-case basis. One of the major concerns in determining sludge application rates will be the prevention of surface water and groundwater pollution at the site considered. In this respect, the energy crop approach is subjected to the same limitations as other methods of land disposal of sludge. Wildlife relying for part of its food on such a site does not represent a major risk to public health for several reasons. First, vegetation grown in the vicinity of the energy crop is likely to constitute only a part of the wildlife diet. Second, wildlife is not a major constituent of the human diet. And, third, the components of wildlife most susceptible to fixing pollutants (liver, kidneys) are often not consumed by humans.

Land disposal of the sludge would also generate a renewable, local source of energy that would reduce the dependence of the local economy on outside energy sources.

Another feature of the energy crop approach is the use of marginal land to produce these crops (i.e., land considered as economically unattractive to produce food crops). Land disposal of sludge would thus not encroach on valuable farmland and would put back into use land presently neglected or abandoned. The energy crop approach also has the potential for reclaiming land such as strip mining areas.

Trade-offs between various costs and credits associated with the method will determine the economic feasibility of sludge disposal on energy crops: Credits for elimination of incineration and/or landfill disposal and from the sale of the energy produced will be received, and expenses for sludge transportation, land use and management, and crop production and conversion will be incurred.

The main task of the study is thus to determine under what circumstances and within what limitations sludge application to energy crops is an economically attractive alternative. These guidelines will then be used to evaluate the impact that the energy crop approach could have on a national scale.

APPROACH TO THE PROBLEM/SCOPE OF WORK

The limited time frame and manpower available for this study did impose some limitations on the scope of the work. The approach is that of a broad-view study concentrating on the principles involved in energy crop production from municipal sludge, rather than on the analysis of specific cases. The specific assumptions made and the approach followed in the study are described below.

1. Estimates will be made for the population and municipal sludge generation rates projected for the year 1985. This year was chosen because most municipalities are expected to have complied with the Federal Water Pollution Control Act Amendments of 1972 (PL 92-500) by that time, and they will have included some form of secondary treatment in their wastewater treatment plants.¹ They would also have in place some form of sludge management.
2. The expected situation is illustrated in Figure 1. The dashed line shows the alternative considered in this report. An anaerobic digestion step is included in the sludge treatment process before land disposal, as some form of stabilization will probably be required by 1985. Other predisposal treatments can be considered before land disposal: such changes in predisposal treatment will have an identical effect on the comparison between the various approaches of disposal on land, as this comparison is performed for the disposal operations occurring below the point marked "Comparison of Disposal Methods" on the figure. The comparison between land disposal and

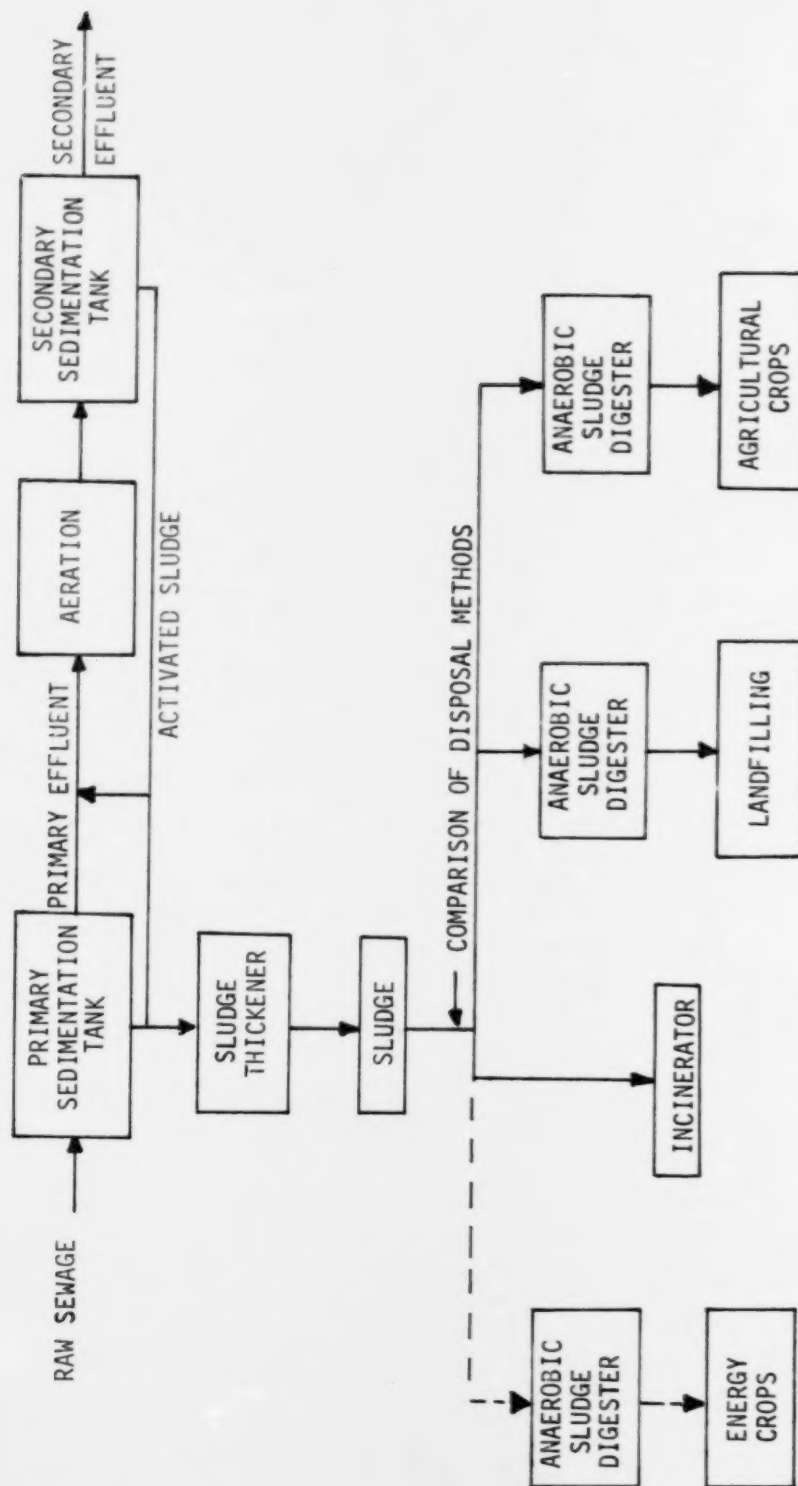


Figure 1. Schematic diagram of an activated sewage treatment plant, including the alternative disposal of sludge through production of energy crops. Source: Reference 2.

incineration could be affected by the replacement of anaerobic digestion by another method of pretreatment. This problem will be addressed by analyzing the sensitivity of the report's conclusions to changes in costs of the various alternatives considered.

Figure 2 describes the general layout of an energy crop plantation used for sludge disposal. The operations include sludge transportation from the wastewater treatment plant to an area where marginal land is available for sludge disposal, storage of the sludge, spreading of the sludge on the parcels of land used for energy crop production, management of the energy crop plantation, conversion of the energy crop to energy, and transportation of the energy produced to its point of use.

The energy crop production option will be compared with three other methods of sludge disposal (i.e., incineration, landfilling, and agricultural crop production).

In the comparison of the energy crop alternative with the three other major methods of disposal of sludge, all operations and costs associated with the energy crop production (as described in Figure 2) will be taken into account. Steps before sludge disposal (primary and secondary treatment) will be assumed to be identical for whatever sludge disposal method is chosen.

3. The potential for land disposal of sludge is estimated for cities of various standard sizes. The rationale for this approach is that it is impossible within the scope of the the program to conduct a city-by-city analysis of the potential for land disposal of sludge. By performing the analysis for standard-sized cities and with the knowledge of the distribution of the population among cities of various sizes, it is possible to obtain a good idea of the potential of the energy crop approach.
4. The assumption is that by 1985, ocean disposal of sludge will have been replaced by incineration, landfilling, or landspreading.
5. Only marginal land (i.e., land in classes 4 and 6 of the National Inventory of Soil and Water Conservation Needs³) will be considered for energy crops. Land in classes 1 to 3 is generally considered as good farm land, and land in classes 5, 7, and 8 is too inclined and too prone to erosion or flooding to be suitable for energy crops. Through sludge application and management, the marginal land will be improved, and thus energy crop production constitutes a form of reclamation of unused land. We should stress, however, that not all land of classes 4 and 6 may be usable for energy crops because of potential erosion or runoff problems. Areas in classes 4E and 6E (E refers to potential erosion problems in the National Inventory³) should be avoided. Reclamation of strip mines or other disturbed land areas is a process extending over a period of time until a steady level of biomass productivity is reached. The analysis presented here does not consider that phase of the reclamation process.

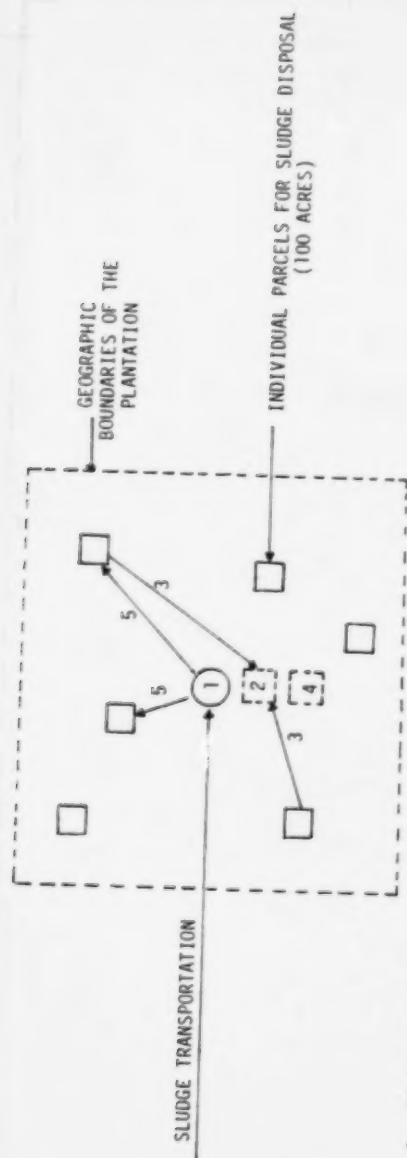


Figure 2. Typical operational layout of an energy crop plantation using sludge as fertilizer for sludge disposal.

However, the conclusions of the report will apply to strip mining areas after they have been brought back to a level of productivity comparable with marginal land.

6. The alternative of producing fiber or saw timber rather than energy crops through disposal of sludge has not been addressed.

METHODOLOGY

The methodology used in the report is illustrated in Figure 3. The municipality is characterized by its population and by the climatic region in which it is located.

The following steps are involved in evaluating the economic feasibility of the energy crop approach. The report will follow these steps in developing the cost and/or credit data.

1. Determine the yearly amount of sludge produced on the basis of population and rate of sludge production.
2. Determine the credit to the municipality if incineration or landfilling of the sludge is replaced by sludge disposal on energy crops. Both credits are functions of the population and include operation and maintenance costs for either method of disposal. Capital recovery costs for the in-place systems (i.e., incineration or landfilling) will still be incurred and thus are not considered as credits. Disposal through agricultural crop production will result in the same credits.
3. Choose energy crops suitable to the climatic region and estimate the crop area required to apply the sludge to the land. This and the following steps of the methodology also apply to disposal on agricultural crops.
4. Determine the storage capacity required on the basis of climatic factors. Estimate the cost of storage, which is a function of population and duration of storage. This and the following steps refer to the energy crop plantation operations as described in Figure 2.
5. Estimate the cost of land application of the sludge.
6. Evaluate the cost of production of the energy crop excluding the cost of land.
7. Estimate the cost of conversion of the crop to energy.
8. Estimate the credit resulting from the sale of the energy produced from the energy crop.
9. Estimate the functional dependence of the sludge transportation cost on the distance from the municipality.

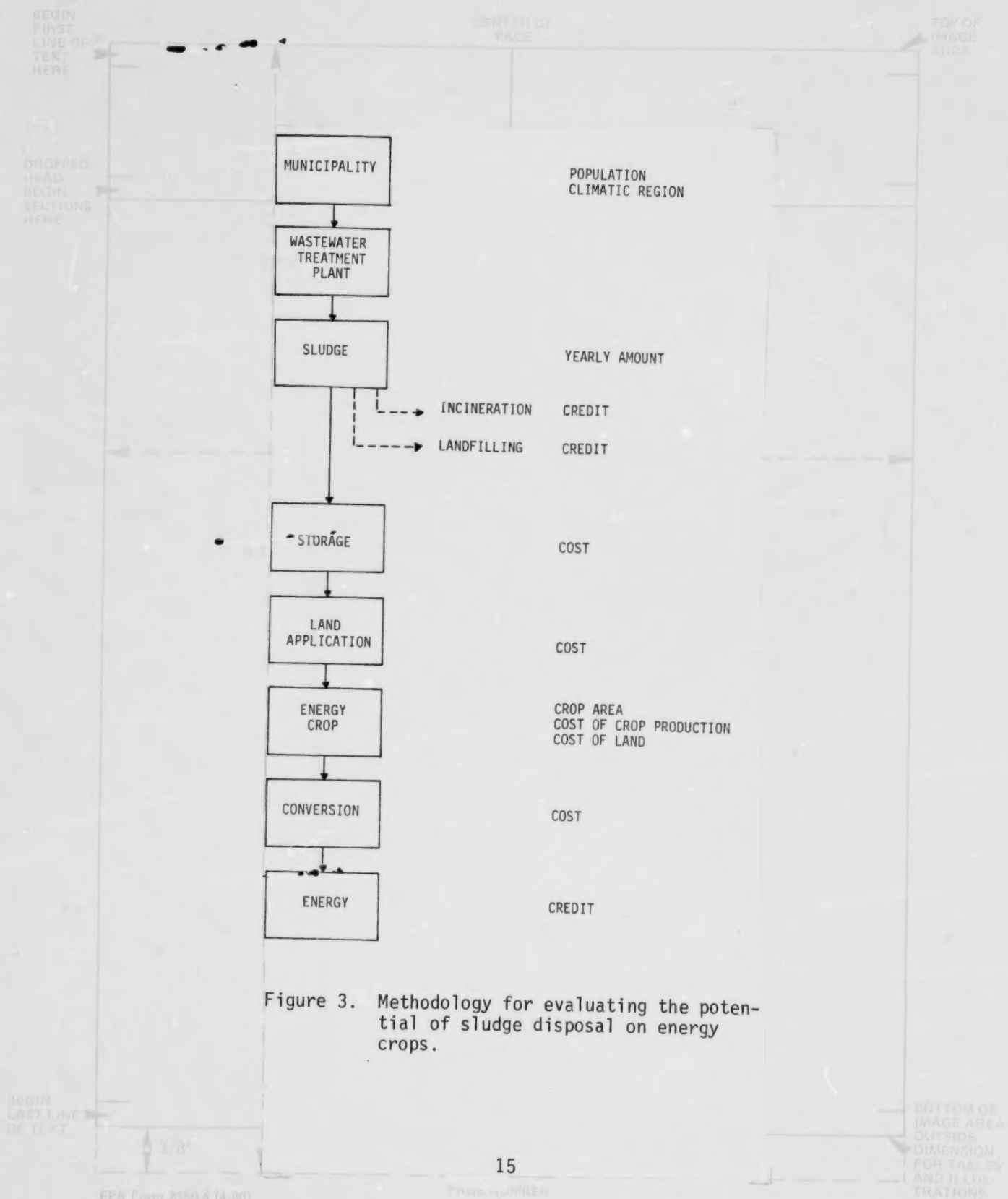


Figure 3. Methodology for evaluating the potential of sludge disposal on energy crops.

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10. Estimate the functional dependence of yearly land costs on the distance from the municipality.
11. Estimate the minimum distance to be traveled from the municipality to find land suitable for sludge disposal.

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The energy crop approach will be economically beneficial if the credits received by the municipality are larger than (or equal to) the sum of the costs incurred in producing the energy crop; thus

$$\begin{aligned} \text{Credit for energy crop} + \text{credit for incineration or landfilling} & \quad (1) \\ & \geq \text{Costs for energy crop production and conversion} \end{aligned}$$

Identifying the terms involved in the total costs for energy crop production (see Figure 3), Equation 1 becomes:

$$\begin{aligned} \text{Credit for energy crop} + \text{credit for incineration or landfilling} & \quad (2) \\ - (\text{Costs for sludge storage, sludge spreading, crop production,} & \\ \text{energy conversion}) & \\ & \geq \text{Sludge transportation cost} + \text{land cost} \end{aligned}$$

All the cost elements on the left-hand side of Equation 2 may be estimated when the population of the municipality and the climatic region in which the municipality is located are known. The two terms in the right-hand side of Equation 2 depend not only on the population, but also on the distance from the city considered: The transportation costs increase with distance, and the land costs decrease with distance. The best location for the plantation is determined by finding the distance at which the sum of the right-hand-side terms is a minimum. If this distance is larger than the minimum distance estimated in step No. 11 (above), the corresponding transportation and land costs will be used in Equation 2. If the distance corresponding to the minimum of the right-hand-side function is smaller than the minimum distance determined in step No. 11, the value of transportation and land costs for the minimum distance estimated in step 11 will be used in Equation 2. Equation 2 can then be used to estimate the economic potential of the energy crop approach compared with other methods of sludge disposal. Similarly, an energy balance can be performed in which the energy credit resulting from the elimination of incineration or landfill operations and from the generation of an energy crop is compared with the amount of energy required to dispose of the sludge and generate the energy crops.

The data base needed to evaluate the various terms of Equations 1 or 2 is generated in the following subsection (Analysis). Section 5 presents the results of the analysis.

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ANALYSIS

Annual Production of Municipal Sludges

In this report, estimates will be made for the population and the municipal sludge generation rates projected for the year 1985. By that time, municipal wastewater treatment plants are expected to have been upgraded to meet the secondary treatment standards defined in the Federal Water Pollution Control Act Amendments of 1972 (PL 92-500) as amended by PL 95-217. With this upgrading, it is assumed that the raw sludge generation rate at that time will be at least 0.104 kg (0.23 lb) per capita-day. Digested sludge for disposal will be generated at a rate of 0.064 kg (0.14 lb) per capita-day. These rates of production are the average rates presently recorded for treatment plants including secondary or tertiary treatment.⁵

A population of 235 million is expected in the United States by 1985. If we assume that by that time about 75% of the population will be sewered and that sludge is produced at the above-mentioned rates, about 6.7 million metric tons (7.4 million short tons) of raw sludge will be produced per year in 1985. The corresponding amount of digested sludge for disposal will be 4.1 million metric tons (4.5 million short tons) per year in 1985. Further details concerning the distribution of sewered population by type of treatment and states are given in Appendix A.

Composition of Municipal Sludge

This study is directed toward planning the immediate future. Consequently, the sludge characteristics to be used in the analysis were selected to reflect the most likely situation in the year 1985. As this point in time, it is assumed that most municipal plants will meet secondary treatment standards--that is, biological treatment for removal of BOD₅ (five-day biological oxygen demand) and suspended solids. The current trend in EPA thinking points toward national standards requiring pretreatment of industrial wastes. For this study, it was assumed that this would be the case.

A wide variation exists in the concentrations of the sludge components (solids, nutrients, persistent organics, and heavy metals) generated by secondary treatment plants. Sommers¹⁰ suggests the use of the median values of the concentrations of sludge components as opposed to the mean values. This approach was adopted in this report: Typical values of sludge components used in the analysis are shown in Table 1.

Cost of Ultimate Disposal of Municipal Sludge

Before 1985, ocean disposal of sludge will be eliminated. Incineration or other thermal conversion processes followed by landfilling of the residues (ashes), landfilling of dewatered digested/stabilized sludge, or land spreading with or without growth of a crop will be the alternative sludge disposal methods available at the time. At present, incineration followed by landfilling and direct landfilling are the methods used for disposal of about 60% of the sludge produced in the United States. As ocean disposal is

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TABLE 1
MEDIAN CONCENTRATIONS OF MAJOR CONSTITUENTS
IN SEWAGE SLUDGE

<u>Component</u>	<u>Type of sludge</u>	
	<u>Anaerobic</u>	<u>Aerobic</u>
	%	
N	4.2	4.8
P	3.0	2.7
K	0.3	0.4
Na	0.7	0.8
Ca	4.9	3.0
Mg	0.5	0.4
Fe	1.2	1.0
Al	0.5	0.4
	mg/kg	
Pb	540	300
Zn	1,890	1,800
Cu	1,000	970
Ni	85	31
Cd	16	16
Cr	1,350	260

Source: Reference 10.

progressively eliminated, it is expected that a larger fraction of the municipal sludges will be incinerated or landfilled.

An analysis of the ultimate cost of sludge disposal by incineration or landfilling as a function of the population of municipalities was performed using data generated in EPA-sponsored studies. The analysis considers the disposal alternatives shown in Figure 1 (i.e., incineration and landfilling). Landspreading without credit for the fertilizer value of the sludge was also included for comparison purposes. Figure 4 summarizes the results of this analysis. Maintenance and operation costs for disposal range from about \$250 to \$25/dry metric ton of sludge as the size of the cities and/or population centers increase from about ten thousand to several million. Note that the costs estimated through the analysis compare fairly well with actual costs reported for treatment plants for cities with populations larger than 100,000. For smaller cities, however, (and particularly for cities smaller than about 50,000) variations of up to about 80% of the costs estimated in the analysis can be expected. Incineration is generally not considered as a viable disposal alternative for cities with population smaller than about 50,000; as a result, the corresponding cost curve (curve 1 on the figure) has not been extended for cities smaller than 50,000. Curve 4 anticipates, somewhat, the results of the analysis: It shows the disposal costs of landspreading when a credit is taken for the fertilizer value of sludge through energy or agricultural crops as compared with the costs of landspreading without credit for the fertilizer value shown on curve 3.

In the approach considered in this study, the disposal of sludge through incineration or landfilling would be replaced by disposal on land devoted to the generation of an energy crop. The maintenance and operation costs of incineration or landfilling become credits in the economic analysis of the method of sludge disposal on energy crops. The same credits apply in the economic evaluation of sludge disposal on agricultural crops.

Sludge Transportation Costs

Sludge transportation from the treatment plant to the point of disposal is a major cost in all sludge-handling schemes. Four major methods of transporting sludges are used and considered in this study: Fixed pipelines and barges for liquid sludges, and tank trucks and rail for hauling either liquid or dewatered sludges.

Annual equivalent costs of transportation (\$/dry metric ton) were derived from an EPA-sponsored study²⁵ for nine different sizes of urban centers (populations of 10,000 to 4 million) for the four transportation methods listed above and for distances extending up to 260 km from the urban centers considered.

The results of the analysis show that:

- a. For small towns and short hauls, trucking of liquid sludge is the most economical system.

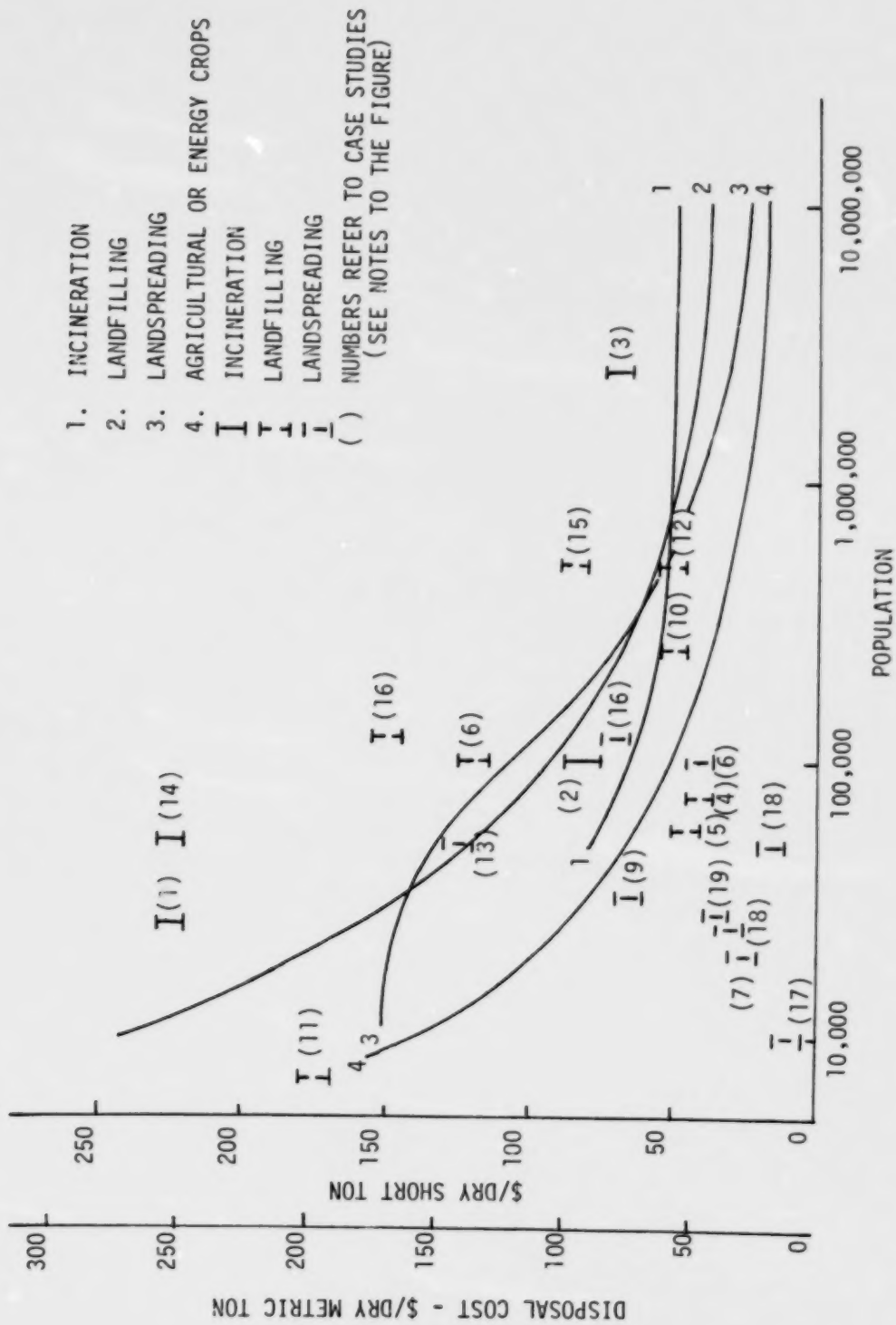


Figure 4. Cost of sludge disposal (operation and maintenance costs, 1977 dollars). See notes on following page.

Notes to Figure 4

Source: Curves: Timothy G. Shea and John D. Stockton - Wastewater Sludge Utilization and Disposal Costs; Technical Report EPA-430/9-75-015, September 1975, MCD-12. U. S. Environmental Protection Agency - A Guide to the Selection of Cost-Effective Wastewater Treatment Systems; Technical Report EPA-430/9-75-002, July 1975. U. S. Environmental Protection Agency - An Analysis of Construction Cost Experience for Waste Water Treatment Plants; EPA-430/9-76-002, February 1976.

Charles E. Pound, Ronald W. Crites, and Douglas A. Griffes - Cost of Wastewater Treatment by Land Application; Technical Report EPA-430/9-75-003, June 1975.

Points:

- (1) Mr. Bruce McDaniel, Sanitary Board, Clarksburg, W. Va. Estimated cost for incineration and disposal.
- (2) and (3) Jerry L. Jones, David C. Bomburger Jr., F. Michael Lewis, and Joel Jacknow - Municipal Sludge Disposal Economics; Environmental Science and Technology 11, No. 10, October 1977; Estimated costs for incineration and landfill.
- (4) through (19) R. Kent Anderson - Cost of Landspreading and Hauling Sludge from Municipal Wastewater Treatment Plants - Case Studies; EPA/530/SW-619, October 1977. Numbers 4 through 19 refer to the following cities:

(4) Anderson, Indiana	(14) Sheboygan, Wisconsin, cost for vacuum filtration and residual disposal excluding incineration
(5) Appleton, Wisconsin	
(6) Bethlehem, Pennsylvania	(15) Toledo, Ohio
(7) Collinsville, Illinois	(16) York, Pennsylvania
(8) Danville, Virginia	(17) Front Royal, Virginia
(9) Ft. Pierce, Florida	(18) Beavercreek Township, Greene County, Ohio
(10) Grand Rapids, Michigan	(19) Lebanon, Pennsylvania
(11) Lawrenceville, Illinois	
(12) Louisville, Kentucky	
(13) Sheboygan, Wisconsin	

Note: Two data points are plotted for some cities when data for both landfilling and landspreading disposal have been generated.

- b. For a distance beyond 30 km, a variety of other methods become cost effective.
- c. For distances beyond 100 km, the hauling of dewatered sludge by rail or barging of liquid sludge becomes the most economical method.
- d. As the town size increases, fixed pipelines become the most economical transport system.

In the forthcoming economic evaluation of sludge disposal on energy crops, the least-cost method of transportation for a given population size and range of distance will be assumed. Actual values of transportation costs are given in Appendix A.

Methods of Sludge Application to Land

Municipal sludge can be spread on the surface of the land or incorporated into it using either liquid or dewatered sludge. The choice of the application method will depend, among other factors, on the type of energy crop being grown. For annual sugar or grain crops, spraying of liquid sludge through fixed or mobile water cannons was chosen as the method of application. This technique could create some runoff problems and does result in some loss of nitrogen.

For woody crops--tree or shrub plantations--subsurface application of liquid sludge was adopted. This method of application does impose some limitations on the minimum spacing between plants to permit passage of the tank trucks between the rows of trees. This restriction on the density of planting is, however, compensated by several advantages: The tillage associated with the subsurface application controls the growth of parasitic weeds competing with the plantation for soil nutrients; little or no nitrogen is lost during sludge application; runoff problems are avoided; and some moisture is incorporated in the soil. The latter factor may be very beneficial during drought periods, but caution should be used during subsurface application to avoid root destruction.

In most regions of the United States, sludge application to the land is limited by climatic factors (i.e., the temperature is below a certain level, precipitation exceeds a certain amount, or snow cover exceeds a certain depth). Earlier work sponsored by EPA led to the definition of five climatic regions in the continental United States. These regions are shown on Figure 5 and are used in the present analysis to characterize the climate-related limitations imposed on land application of sludge. Briefly, the five regions are: Region A: California; Region B: Nevada, Utah, New Mexico, Arizona, and the western half of Texas; Region C: the States south of the northern border of Virginia, Tennessee, Kentucky, Oklahoma, and east of the Oklahoma panhandle; Region D: the States east of and including Colorado, north of Region C, and south of the Great Lakes and Northern States (the corn belt is included in this region); and Region E: the Northern and Lake States constituting the major grain-producing regions.



- A - Mediterranean Climate-Dry summer-mild, wet winter
- B - Arid Climate-hot, dry
- C - Humid Subtropical-mild winter-hot, wet summer (Wash., Ore., area mild, moist summer)
- D - Humid Continental-short winter, hot summer
- E - Humid Continental-long winter, warm summer

Figure 5. Climatic regions. (Source: Reference 27.)

Land Cost and Land Availability

Land costs and sludge transportation costs are important to the economics of the production of energy crops. An analysis was made to determine how land costs vary as distance increases from population centers. Land cost/distance curves were derived for cities with populations larger than 3 million, 1 to 3 million, 500,000 to 1 million, and 100,000 to 500,000. The analysis also showed that the curve for the last category of cities could be used for cities with populations of less than 100,000. The four land cost/distance curves are shown in Figure 6. These curves show that one must travel about 40 km (25 miles) from centers with populations of 100,000 to 500,000 to find land at a cost approaching the national average of the value of land and buildings in farms (i.e., about \$740/ha, or \$300/acre). This distance increases to 80 km (50 miles), 130 km (80 miles), and 320 km (200 miles) for cities of 500 to 1 million, 1 to 3 million, and more than 3 million, respectively. The method of analysis is discussed in Appendix A.

Land disposal of municipal sludge on energy crops assumes that land will be available for growing these crops within a reasonable distance of the city of interest. An analysis was performed to determine how far it is necessary to haul sludge to find enough land to dispose of this sludge.

The criterion used to determine the minimum distance for hauling the sludge from a city was the distance from the city at which 90% of the land is classified as farmland. This criterion was adopted because it was felt that the influence of rural or suburban development or industrial expansion on land cost and land availability would be negligible in areas where about 90% of the land is classified as farmland. One must travel about 30 km (20 miles) from cities with populations of 100,000 to 200,000 to find any counties in which 90% or more of the county area is farmland. This distance increases to 40 km (25 miles) and 50 km (30 miles) for cities with populations of 500,000 to 1 million and for cities larger than 1 million, respectively. For cities smaller than 100,000 the minimum distance decreases progressively until it reaches about 8 km (5 miles) for cities of 10,000. These distances are estimates that will have to be better defined for specific case studies.

One of the major assumptions of this study is that energy crops will only be grown on marginal farmland (i.e., land classified as farmland but not intensively used or suitable for that purpose). An analysis of the distribution of farmland by productivity categories showed that marginal land usable for energy crops represents about 15% of the total farmland. The study assumed that the energy farm was made of individual parcels of marginal land of about 40 ha (100 acres) each, distributed at random within a geographic area. This land distribution factor has a strong bearing on transportation of equipment, supplies, and crops in the course of operating the energy farm. This 40-ha parcel size is probably a "worst case," as it is expected that larger tracts of marginal land will be available for sludge disposal. This parcel size will have to be adjusted for site-specific cases.

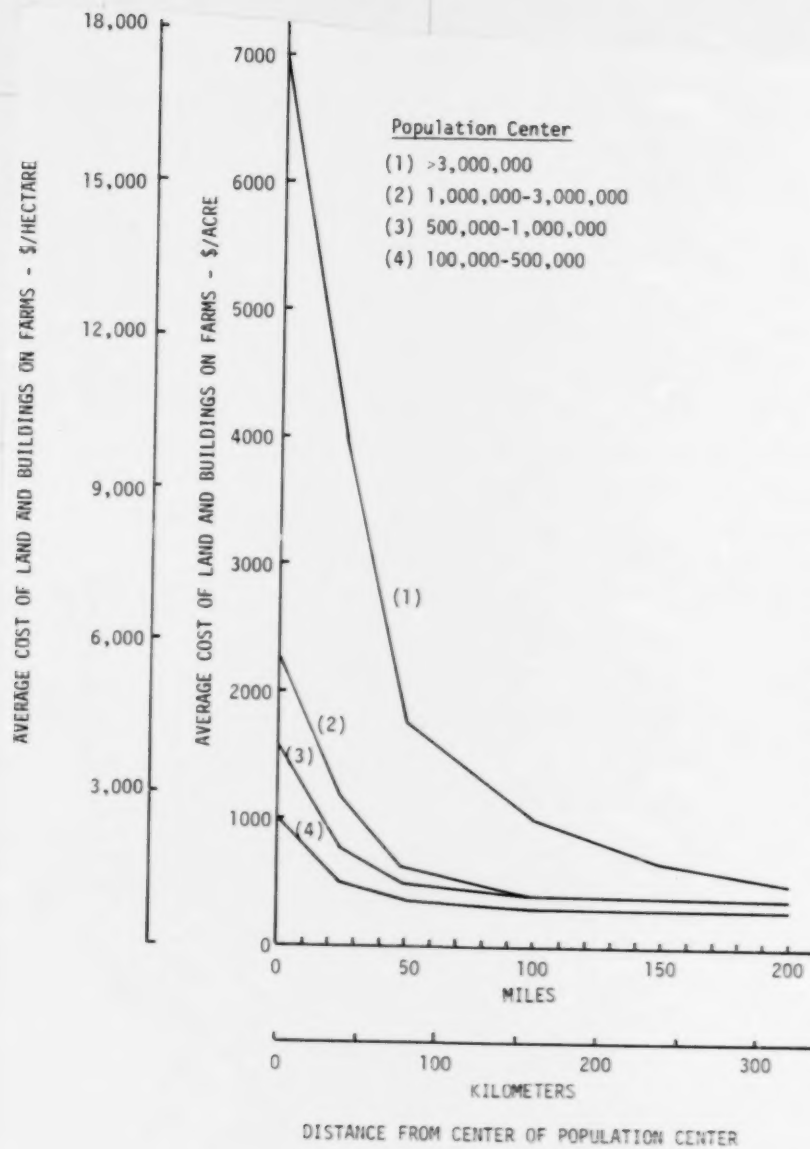


Figure 6. Cost of land as a function of distance from metropolitan center.

Potential Energy Crops - Growth Areas

Four classes of energy crops were retained in the analysis: Hardwoods grown on short rotations, sugar crops (beets, sorghum), grain crops, and desert or arid land shrubs. Softwoods could replace hardwoods in some situations, but a previous analysis has shown that the economics of softwood plantations are less favorable than those of hardwoods. The areas of growth of these crops are: Regions C, D, and E (northern and Lake States and eastern half of the United States) for hardwoods (and softwoods if warranted), regions D and E for grain crops (grain-growing region), regions C and part of region D for sugar crops (central and southeastern region) and regions A and B (California and southwest) for arid land shrubs. The crop and land characteristics are further described in Appendix A.

Selected Energy Crops and Conversion Methods

The four classes of energy crops listed in the preceding subsection may be used in a number of ways to generate energy: Direct combustion or conversion to gaseous, liquid, or solid fuels. In this analysis, only conversion processes relying on existing technology were considered. To evaluate the feasibility of producing energy crops from sludge, the following crop uses were considered: (1) The use of biomass from hardwood or arid-land shrub plantations either directly as fuel for process heat or as fuel to generate electricity, and (2) the use of sugar and grain crops to produce ethanol fuel. Because of the economy of scale achieved in large conversion plants, the production of ethanol fuel or electricity is only economically attractive for large plantations if all the raw material needed by the conversion plant (wood chips or sugar or grain crops) is supplied by the energy farm. For the application rates of liquid sludge recommended for hardwood crops (about 11 metric tons/ha or 5 tons/acre on a dry basis [see Appendix A7]) and the productivities expected from these crops (about 18 oven-dry metric tons/ha-year or 8 oven-dry tons/acre-year), sufficient wood chips are produced by population centers of 2 million or more to support an electric power plant of about 20 MW. Electricity generation from wood chips will thus be included as a possible alternative for large cities. Wood chip production for fuel--direct combustion for process heat--or other uses is an alternative for cities of any size. Because of the higher sludge application rates required by sugar and grain crops and the large capacity required for economic reasons for ethanol conversion plants, the minimum population needed to support one such ethanol conversion plant would be 5 million or more for sugar crops and about 50 million for grain crops if all the raw material for conversion is supplied by the energy farm.

Table 2 shows the conversion processes and energy crops considered in the analysis. The last two columns give the estimated present-day value of these energy crops or their conversion products. The present-day value of an item is its value expressed in 1977 dollars increased by an appropriate factor for the period 1977-85 but excluding normal inflation. For instance, it is expected ⁴⁹ that the cost of electricity will increase in the near term at a rate 3% higher than the normal rate of inflation during that period. The cost quoted in the table reflects this additional increase of 3%. The present-day values in the table thus represent the expected market value

TABLE 2

SELECTED CONVERSION PROCESSES AND FORMS OF ENERGY CROP
CONSIDERED IN THE ANALYSIS AND THEIR PRESENT DOLLAR VALUE(1)
COMPARED WITH PRESENT DOLLAR VALUE(1) OF FOSSIL FUELS USED IN 1985

Energy Crop	Product and Usage	\$/Metric Ton(2)	\$/10 ⁶ Btu(6)
Wood	Wood chips as raw material	\$11.00	---
	Wood chips as fuel	---	\$1.00(3)
	Wood chips to electricity	---	8(4) to 40(4)
Sugar Crop	Ethanol	---	20.00(5)
Grain Crop	Ethanol	---	20.00(5)
Fossil Fuels			
Coal	---	---	(0.58)(8) to 1.00-1.32(7)
Oil	---	---	2.94 to 3.84(7)
Natural Gas	---	---	1.92 to 5.88(7)

(1) Present dollar value of fuels or energy used in 1985 is the value of fuels or energy expressed in 1977 dollars adjusted for the expected price increases of these items over the price increase resulting from normal inflation.⁴⁹

(2) Excluding transportation.

(3) This cost corresponds to the presently practiced cost of \$35/cord (air dry) for firewood delivered in rural areas. In suburban areas, the cost of firewood delivered reaches \$70/cord, or about \$2/10⁶ Btu.

(4) Range of values corresponding to cost of electricity of 2¢ to 10¢/kWh, adjusted by a 3% increase factor to 1985 but excluding normal inflation.

(5) Market value of \$0.30/liter (\$1.14/gal) adjusted by a 3% increase factor to 1985 but excluding normal inflation and energy content of 72,190 Btu/gal (5% H₂O).

(6) Multiply values by 0.95 to obtain \$/GJ.

(7) Range of values for the five climatic regions shown in Figure 5.

(8) Present-day value for climatic region B - southwestern states.

(expressed in 1977 dollars) of the various forms of energy used in 1985 and will be used to estimate the credit resulting from the sales of the energy crops or their conversion products.

The bottom part of the table reports expected present-day values of fossil fuels. The range of values quoted covers the variation in costs expected in the five climatic regions of Figure 5 for these fuels. If the value of wood chips for fuel (\$1/10⁶ Btu) is compared with that of fossil fuels, it is apparent that the wood chips are competitive with oil and gas on an energy-content basis. The lower expected value for coal (\$0.58/10⁶ Btu) is for climatic region B (the Southwest), where wood chips are not expected to be competitive with coal. In the other regions where the range of coal costs is expected to be from about \$1 to \$1.32/10⁶ Btu, wood chips used locally would be competitive with coal. This conclusion is reinforced by quotes for present-day prices of low-sulfur coal of about \$1.36/10⁶ Btu (\$30/ton) in Michigan^{68,69} and about \$3.63/10⁶ Btu (\$80/ton) in New York State⁷⁰. Thus for equal power plant sizes and for most regions of the country, electricity could be generated from wood chips at prices equal to or lower than those of coal-fired power plants.

Nutrients and Water Balance - Rate of Sludge Application

High-yielding energy crops can only be grown on a sustained basis if sufficient water and nutrients are available to the plantation during each growing season. The nutrient balance for each candidate energy crop will in turn determine the rate of sludge application to the land and thus the land area required to dispose of the sludge for a given population size.

An analysis of the water and nutrient demand for the four classes of energy crops considered and the five climatic regions was performed. The analysis showed that hardwood plantations can be grown at a rate of about 18 oven-dry metric tons/ha·year (8 oven-dry tons/acre·year) in most areas of regions C, D, and E with no irrigation and a sludge (5% solids) application rate of 10 to 15 dry metric tons/ha·year (4.5 to 8 dry tons/acre·year). Yields comparable to the ones mentioned above have been recorded in various areas of the United States with species such as hybrid poplars, sycamore, cottonwood and eucalyptus. Sugar and grain crops can be grown successfully in many areas of the same climatic regions with no irrigation but with sludge (5% solids) application rates of 20 to 28 dry metric tons/ha·year (9 to 12.5 dry tons/acre·year). Regions A and B--California and the southwestern states--require irrigation to grow hardwoods or agricultural energy crops. Arid land or desert shrubs adapted to the climatic conditions of Regions A and B were adopted as energy crops for those regions. No data were found concerning the response of these species to management and fertilization. A yield of 11 oven-dry metric tons/ha·year (5 oven-dry tons/acre·year) is assumed, which is about twice the yield of unmanaged natural stands. The nutrient requirements were assumed to be identical on a biomass production basis to those of hardwoods. Because of this uncertainty in productivity of biomass from arid land shrubs, the impact of changes in productivity of shrub plantations in regions A and B on the economic feasibility of the concept is examined in the sensitivity analysis section.

Production Costs of Energy Crops and Energy

The conceptual layout of an energy crop plantation is shown on Figure 2. For woody energy crops, each of the parcels making up the plantation is planted with fast-growing deciduous species such as hybrid poplars, sycamore, or cottonwood. During their growth periods between harvests, the plantations are managed in very much the same way as agricultural crops: Weed control, fertilizer (sludge) application, and fungicide application. The plantations are harvested on a short rotation cycle (3 to 6 years). After a first harvest, the roots of deciduous species will resprout and produce another biomass crop from the same original planting. It is estimated that with appropriate management, up to about five coppice (or regrowth) harvests can be produced from an original planting. With few exceptions, conifers do not resprout from their roots and will require replanting after each harvest.

The computer model established earlier by InterTechnology/Solar Corporation and described in Appendix B was used to evaluate the cost of woody crop production delivered in the form of wood chips. The cost estimates include all costs associated with the plantation operation--seedling, planting, cultivation, harvesting, chipping, transportation within the plantation area, sludge storage, sludge application, fuels and supplies, and management--except sludge transportation to the plantation and land costs, which are estimated separately (see earlier subsections on sludge transportation costs and land costs and availability). Production costs for chips range from a high of about \$33/oven-dry metric ton (\$30/oven-dry ton) for small cities (with populations of about 10,000) to a low of about \$11/oven-dry metric ton (\$10/oven-dry ton) for cities of 1 million or more. These costs are comparable to those practiced by wood-lot operators at present. As mentioned earlier, electricity can be produced from energy crop plantations serving population centers of about 2 million or more. The cost of production is estimated to be about \$0.07 per kWh (\$20/10⁶ Btu), which compares to the projected costs of electricity for 1985 (see Table 2, Note 4). In the plantation model used, the ashes produced by the combustion of the chips are returned to the plantation and spread on the land for their nutrient (phosphorus, potassium, calcium) and soil-conditioning value. The cost of ash recycling and spreading is included in the model. Estimated production costs of sugar crops range from \$26/dry metric ton (\$24/dry ton) for sorghum to \$57/dry metric ton (\$52/dry ton) for sugar beets, excluding land and sludge transportation costs. These crop costs result in ethanol production costs of about \$0.32/liter (\$1.21/gal) for large ethanol production plants.

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SECTION 5

RESULTS OF THE ANALYSIS

ECONOMIC FEASIBILITY OF THE ENERGY-CROP-FROM-SLUDGE CONCEPT

One of the major factors that will determine the attractiveness of the energy-crop-from-sludge concept is its economic implication for the cities and municipalities involved. The methodology proposed in Section 4 was applied to cities of various populations using the data base generated in the same section.

Woody Energy Crops for Fuel

The economic feasibility of sludge disposal on land devoted to the production of woody fuel crops was evaluated for cities with populations of 10,000 to 4 million. The analysis involves the following steps:

- a. Estimate the yearly sludge production on the basis of the population.
- b. Determine the land area required on the basis of the climatic region considered and the rates of sludge application required by the crop considered.
- c. Determine the cost of energy crop production. The model described in Section 4 and Appendix B is used for this purpose. The cost includes the costs for all plantation operations, sludge storage, and sludge application, but not the costs for sludge transportation and land.
- d. Estimate the minimum combined cost for sludge transportation and land for given population and plantation sizes.
- e. Estimate the yearly credit resulting from the sale of the energy crop or the energy produced.
- f. Estimate the yearly credit (yearly operation and maintenance costs) resulting from the elimination of incineration and/or landfilling.
- g. Estimate the net dollar balance equal to the sum of the credits (items e and f) minus the sum of the costs involved in the energy crop production (items c and d). A positive balance

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indicates that the energy crop approach is more attractive economically than incineration and/or landfilling.

A similar procedure (items a to e) is followed to estimate the costs and credits resulting from sludge disposal on land used to produce agricultural crops. The differences between the credit and cost for both the energy crop and the agricultural crop are then compared to estimate the net dollar balance between these two methods of sludge disposal. A positive balance indicates that the energy crop approach is more attractive economically than the agricultural crop approach and vice versa. The results of the analysis are summarized in Tables 3 through 7.

Item 4 in the tables--agricultural crop production costs--was estimated through the procedure indicated above. The agricultural crops chosen for these estimates were: silage sorghum for Regions A (California) and B (Southwest)⁷¹, grain sorghum for Region C (Southwest)³⁹ and grain corn for Regions D and E (North, Central, Northeast, and North Central)⁴⁰.

Item 5d in the tables (credit for agricultural crops) was estimated on the basis of U.S. Department of Agriculture agricultural prices data.⁶⁷ The range of prices quoted in the table correspond to the range of prices for agricultural products reported in 1977.

Items 6a and 6b in the tables show the yearly cost of disposal of sludge via energy crops and agricultural crops, respectively. These yearly amounts should be compared with the yearly operation and maintenance costs for the other methods of disposal--that is, incineration (item 5b) and landfilling (item 5c).

Item 8 in the tables--capital investment--is the capital investment required to implement the energy crop method of disposal. For cities with populations smaller than about 1 million, the capital investment includes sludge transportation equipment and sludge storage facilities and land purchase; the plantation operations are assumed to be subcontracted to local operators. For cities larger than 1 million, the capital investment includes sludge transportation equipment and sludge storage facilities, land purchase, and all plantation equipment. In this case, the energy crop plantation is assumed to be managed by the city or one of its agencies. The capital investment for implementing sludge disposal on agricultural crops is similar to that for disposal on energy crops, as in both cases the same type of equipment and operations are involved.

Item 8a is the capital investment required to implement the energy crop method of disposal when an anaerobic digester is already in place to pretreat the sludge before land disposal. This situation is most likely to occur when landfilling or landspreading on agricultural crops is the method already used for sludge disposal.

Item 8b is the capital investment required to implement the energy crop method of disposal when an anaerobic digester must be installed to pretreat the sludge before its disposal on the land. This situation is most likely to occur when the in-place method of sludge disposal is incineration. In this

TABLE 3

ECONOMIC ANALYSIS OF THE PRODUCTION OF WOOD CHIPS FROM LAND USED FOR SLUDGE DISPOSAL
CLIMATIC REGION A (CALIFORNIA)

1. Population	10,000	50,000	200,000	700,000	4,000,000
2. Sludge-dry metric tons/y	232	1,159	4,635	16,222	92,695
3. Biomass Production Costs:					
a. Plantation operation - 10 ³ \$/y	18	40	116	345	1,752
b. Sludge transportation and land costs - 10 ³ \$/y	21	59	318	609	3,809
c. Total - 10 ³ \$/y	39	99	434	954	5,561
4. Agricultural crop production costs - 10 ³ \$/y	26	84	388	770	4,434
5. Credits:					
a. Biomass sale - 10 ³ \$/y	8	38	152	532	3,042
b. Incineration - 10 ³ \$/y	-	102	296	930	5,110
c. Landfilling - 10 ³ \$/y	61	153	373	930	4,088
d. Agricultural crop sale - 10 ³ \$/y	11-14	57-70	228-281	798-983	4,558-5,617
6. Cost of disposal through:					
a. Energy crop (3c-5a)-10 ³ \$/y	31	61	282	422	2,519
b. Agricultural crop (4-5d)-10 ³ \$/y	15-12	27-14	160-107	-28--213	-124--1,183
7. Net dollar balance versus:					
a. Incineration (5a+5b-3c)-10 ³ \$/y	-	41	14	508	2,591
b. Landfilling (5a+5c-3c)-10 ³ \$/y	30	92	91	508	1,569
c. Agricultural crops (5a-3c-5d+4)-10 ³ \$/y	-16--19	-34--47	-122--175	-450--635	-2,643--3,702
8. Capital investment for energy or agricultural crops:					
a. Without anaerobic digestion - 10 ³ \$	27	137	2,669	7,134	53,596
b. With anaerobic digester - 10 ³ \$	-	413	3,398	8,884	59,529
9. Yearly operating and capital costs of pretreatment anaerobic digester - 10 ³ \$/y - in conjunction with situation 8b	-	32	80	197	751
10. Net dollar balance versus incineration when a pretreatment digester must be included (5a+5b-3c-9)-10 ³ \$/y	-	9	-66	311	1,840

TABLE 4

ECONOMIC ANALYSIS OF THE PRODUCTION OF WOOD CHIPS FROM LAND USED FOR SLUDGE DISPOSAL
CLIMATIC REGION B (SOUTHWEST)

	10,000	50,000	200,000	700,000	4,000,000
1. Population					
2. Sludge-dry metric tons/y	232	1,159	4,635	16,222	92,695
3. Biomass production costs:					
a. Plantation operation - 10 ³ \$/y	18	35	99	289	1,518
b. Sludge transportation and land costs - 10 ³ \$/y	21	57	306	538	3,398
c. Total - 10 ³ \$/y	39	92	405	827	4,916
4. Agricultural crop production costs - 10 ³ \$/y	25	78	364	670	3,913
5. Credits:					
a. Biomass sale - 10 ³ \$/y	6	31	125	439	2,505
b. Incineration - 10 ³ \$/y	-	102	296	930	5,110
c. Landfilling - 10 ³ \$/y	61	153	373	930	4,088
d. Agricultural crop sale - 10 ³ \$/y	12-14	58-71	232-286	811-999	4,636-5,712
6. Cost of disposal through:					
a. Energy crop (3c-5a)-10 ³ \$/y	33	61	280	388	2,411
b. Agricultural crop (4-5d)-10 ³ \$/y	13-11	20-7	132-78	-141--329	-723--1,799
7. Net dollar balance versus:					
a. Incineration (5a+5b-3c)-10 ³ \$/y	-	41	16	542	2,699
b. Landfilling (5a+5c-3c)-10 ³ \$/y	28	92	93	542	1,677
c. Agricultural crops (5a-3c-5d+4)-10 ³ \$/y	-20--22	-41--54	-148--202	-529--717	-3,134--4,210
8. Capital investment for energy or agricultural crops:					
a. Without anaerobic digester - 10 ³ \$	23	113	2,482	6,288	47,155
b. With anaerobic digester - 10 ³ \$	-	389	3,211	8,038	53,088
9. Yearly operating and capital costs of pretreatment anaerobic digester in conjunction with situation 8b-10 ³ \$/y	-	32	80	197	751
10. Net dollar balance versus incineration when a pretreatment digester must be included (5a+5b-3c-9)-10 ³ \$/y	-	9	-64	345	1,948

TABLE 5

ECONOMIC ANALYSIS OF THE PRODUCTION OF WOOD CHIPS FROM LAND USED FOR SLUDGE DISPOSAL
CLIMATIC REGION C (SOUTHEAST)

1. Population	10,000	50,000	200,000	700,000	4,000,000
2. Sludge-dry metric tons/y	232	1,159	4,635	16,222	92,695
3. Biomass production costs:					
a. Plantation operation - 10 ³ \$/y	19	40	106	298	1,363
b. Sludge transportation and land costs - 10 ³ \$/y	20	41	259	464	2,839
c. Total - 10 ³ \$/y	39	81	365	762	4,202
4. Agricultural crop production costs - 10 ³ \$/y	27	74	384	876	5,107
5. Credits:					
a. Biomass sale - 10 ³ \$/y	7	21	142	497	2,839
b. Incineration - 10 ³ \$/y	-	102	296	930	5,110
c. Landfilling - 10 ³ \$/y	61	153	373	930	4,088
d. Agricultural crop sale - 10 ³ \$/y	9-11	46-57	184-227	645-794	3,684-4,535
6. Cost of disposal through:					
a. Energy crop (3c-5a)-10 ³ \$/y	32	60	223	265	1,363
b. Agricultural crop (4-5d)-10 ³ \$/y	18-16	28-17	200-157	231-82	1,423-572
7. Net dollar balance versus:					
a. Incineration (5a+5b-3c)-10 ³ \$/y	-	42	23	665	3,747
b. Landfilling (5a+5c-3c)-10 ³ \$/y	29	93	92	665	2,725
c. Agricultural crops (5a-3c-5d+4)-10 ³ \$/y	-14--16	-32--43	-23--66	-34--183	60--791
8. Capital investment for energy or agricultural crops:					
a. Without anaerobic digester - 10 ³ \$	16	80	2,228	5,138	38,388
b. With anaerobic digester - 10 ³ \$	-	356	2,957	6,888	44,321
9. Yearly operating and capital costs of pretreatment anaerobic digester in conjunction with situation 8b-10 ³ \$/y	-	32	80	197	751
10. Net dollar balance versus incineration when a pretreatment digester must be included (5a+5b-3c-g)-10 ³ \$/y	-	10	-57	468	2,996

TABLE 6

ECONOMIC ANALYSIS OF THE PRODUCTION OF WOOD CHIPS FROM LAND USED FOR SLUDGE DISPOSAL
CLIMATIC REGION D (CENTRAL AND EAST CENTRAL STATES)

1. Population	10,000	50,000	200,000	700,000	4,000,000
2. Sludge-dry metric tons/y	232	1,159	4,635	16,222	92,695
3. Biomass production costs:					
a. Plantation operation - 10 ³ \$/y	21	38	98	267	989
b. Sludge transportation and land costs - 10 ³ \$/y	20	54	285	456	2,667
c. Total - 10 ³ \$/y	41	92	383	723	3,656
4. Agricultural crop production costs - 10 ³ \$/y	23	69	337	615	3,498
5. Credits:					
a. Biomass sale - 10 ³ \$/y	6	31	124	434	2,378
b. Incineration - 10 ³ \$/y	-	102	296	930	5,110
c. Landfilling - 10 ³ \$/y	61	153	373	930	4,088
d. Agricultural crop sale - 10 ³ \$/y	4-5	21-26	85-106	299-371	1,710-2,117
6. Cost of disposal through:					
a. Energy crop (3c-5a)-10 ³ \$/y	35	61	259	289	1,278
b. Agricultural crop (4-5d)-10 ³ \$/y	19-18	48-43	252-231	316-244	1,788-1,381
7. Net dollar balance versus:					
a. Incineration (5a+5b-3c)-10 ³ \$/y	-	41	37	641	3,832
b. Landfilling (5a+5c-3c)-10 ³ \$/y	26	92	114	641	2,910
c. Agricultural crops (5a-3c-5d+4)-10 ³ \$/y	-16--17	-13--18	-7--28	-27--45	510-103
8. Capital investment for energy or agricultural crops:					
a. Without anaerobic digester - 10 ³ \$	14	70	2,149	4,782	35,678
b. With anaerobic digester - 10 ³ \$	-	346	2,878	6,532	41,611
9. Yearly operating and capital costs of pretreatment anaerobic digester in conjunction with situation 8b - 10 ³ \$/y	-	32	80	197	751
10. Net dollar balance versus incineration when a pretreatment digester must be included (5a+5b-3c-9) 10 ³ \$/y	-	9	-43	444	3,081

TABLE 7

ECONOMIC ANALYSIS OF THE PRODUCTION OF WOOD CHIPS FROM LAND USED FOR SLUDGE DISPOSAL
CLIMATIC REGION E (NORTHWESTERN, NORTHCENTRAL AND NORTHEASTERN STATES)

	10,000	50,000	200,000	700,000	4,000,000
1. Population					
2. Sludge-dry metric tons/y	232	1,159	4,635	16,222	92,695
3. Biomass production costs:					
a. Plantation operation - 10 ³ \$/y	20	38	97	268	1,358
b. Sludge transportation and land costs - 10 ³ \$/y	20	54	284	448	2,645
c. Total - 10 ³ \$/y	40	92	381	716	4,003
4. Agricultural crop production costs - 10 ³ \$/y	23	68	335	604	3,461
5. Credits:					
a. Biomass sale - 10 ³ \$/y	6	30	122	426	2,433
b. Incineration - 10 ³ \$/y	-	102	896	930	5,110
c. Landfilling - 10 ³ \$/y	61	153	373	930	4,088
d. Agricultural crop sale - 10 ³ \$/y	4-5	20-25	79-98	278-343	1,588-1,962
6. Cost of disposal through:					
a. Energy crop (3c-5a)-10 ³ \$/y	34	62	259	290	1,570
b. Agricultural crop (4-5d)-10 ³ \$/y	19-18	48-43	256-237	326-261	1,873-1,499
7. Net dollar balance versus:					
a. Incineration (5a+5b-3c)-10 ³ \$/y	-	40	37	640	3,540
b. Landfilling (5a+5c-3c)-10 ³ \$/y	27	91	114	640	2,518
c. Agricultural crops (5a-3c-5d+4)-10 ³ \$/y	-15--16	-14--19	-3--22	36-29	303--71
8. Capital investment for energy or agricultural crops:					
a. Without anaerobic digester - 10 ³ \$	14	68	2,140	4,739	35,346
b. With anaerobic digester - 10 ³ \$	-	344	2,869	6,489	41,279
9. Yearly operating and capital costs of pretreatment anaerobic digester in conjunction with situation 8b - 10 ³ \$/y	-	32	80	197	751
10. Net dollar balance versus incineration when a pretreatment digester must be included (5a+5b-3c-9)-10 ³ \$/y	-	8	-43	443	2,789

situation, anaerobic pretreatment becomes a prerequisite for implementation of the energy crop approach. The capital costs were obtained from reference 21.

Item 9 represents the yearly costs for capital retirement and operation of the pretreatment anaerobic digester where it is not in place (see Item 8b). These costs become part of the operating costs of sludge disposal on energy crops and should be added to item 6a when a digester must be added for sludge pretreatment.

Item 10 is the net dollar balance versus incineration when a digester is not in place but must be added as a pretreatment step before disposal of the sludge on energy crops. In-place landfilling disposal methods would probably have in-place pretreatment and would not require building a new digester before sludge disposal on energy crops. The comparison between the energy crop approach and an existing system was thus restricted to an in-place incineration system in this case.

The results show that:

- a. For all regions, the production costs for energy crops (item 3c in the tables) and for agricultural crops (item 4) are comparable. This is expected, as the sludge handling and field operations are similar in both cases.
- b. Based on present-day prices, the credits for the sale of agricultural crops are higher than the credits for biomass for fuel sales for sorghum-type crops (Tables 3, 4, and 5; items 5a and 5d) and lower for corn crops (Tables 6 and 7; items 5a and 5d). Because of the fluctuations in prices paid to farmers for their product, the potential credit resulting from the sale of agricultural crops may vary widely, as shown in line 5d of the tables.

The credits for agricultural crops are equal to the prices paid to the farmer for the crops produced on land used for sludge disposal. During the 1975-77 period, prices paid to farmers for the products considered here have only increased to an annual rate of about 0.25%,⁶⁷ well below the general inflation rate of 5% to 6% recorded during the same period. If the same trend is maintained in the years to come, by 1985 (the year used for the basis of the economic comparison of this section), the value of the credits for agricultural crops expressed in 1977 dollars will only be about 65% of the values quoted in the tables.

- c. From items 6a and 6b in the tables, it is apparent that after credit is taken for the sale of those crops produced in either case, the cost of sludge disposal on agricultural crops is generally lower than the cost of disposal through generation of energy crops. However, in view of the large fluctuations in the prices paid for agricultural crops and the lag of farm prices with respect to inflation as discussed above, the economic advantage

of disposal on agricultural rather than energy crops could be much smaller than indicated in the tables or altogether eliminated by 1985. In addition, it is uncertain at this time whether EPA will impose market limitations on sludge-grown crops that would also affect price.

- d. The total crop production costs, i.e. plantation operations (item 3a in the tables) plus sludge transportation and land costs (item 3b in the tables) exceed the market value of the biomass (item 5a). The major reason for this is the high cost of sludge transportation (5% solids) to the site of the plantation: A detailed analysis shows that these transportation costs are the highest part of item 5b in the tables and may account for 80% of the combined transportation and land costs in the case of small cities.
- e. The credit for the sale of biomass (item 5a in the tables) is estimated on the basis of a sale price for wood chips of \$11/metric ton (\$10/short ton) (green)--that is, current price for chips for the pulp industry, or about \$0.95/GJ (\$1.00/10⁶ Btu). As discussed in Section 4 (Table 2), at this price wood chips for fuel are competitive with oil, natural gas, and coal in many parts of the country. But the cost of energy from biomass as calculated from the production costs and transportation and land costs shown in the tables varies significantly with the climatic regions and the size of the cities, as is apparent in Table 8. The cost of energy within a given region is a complex function of the population: As population increases, unit production costs decrease, but land and sludge transportation costs increase. Also, for the smaller cities, the minimum of the combined land and sludge transportation costs is not reached, since the minimum haul distance to suitable plantation land is greater than the distance for which the minimum land plus transportation cost is reached. The costs shown in Table 8 are the price at which wood chips should be sold to offset completely the cost of sludge disposal through energy crops.

If the top section of Table 8 is compared with the bottom section, it is apparent that on a \$/Btu basis, energy from wood chips is competitive (1985 basis) with oil for cities with populations of 25,000 or more in Regions A, B, and C and for cities of 50,000 or more in Regions D and E. Similarly, energy from biomass is competitive with natural gas for all city sizes in Region A, and for cities with populations of more than 10,000 and 25,000 in Regions B and D. In none of the regions is energy from biomass competitive with coal under the conditions considered in the table. Thus if biomass could be sold as alternative fuel at prices comparable with those of oil or gas (on an energy content basis) in locations where coal is difficult to obtain, the economic position of the energy-crop-from-sludge approach would be even more favorable than shown in Tables 3

TABLE 8
COST OF ENERGY IN THE FORM OF WOOD CHIPS REQUIRED TO OFFSET COMPLETELY
ALL COSTS OF SLUDGE DISPOSAL (\$10⁶ Btu)(1)

Region	Population (10 ³)							
	10	25	50	100	200	350	700	2,000
A	4.98	2.90	2.52	2.93	2.76	1.95	1.74	1.45
B	6.05	3.65	2.85	3.34	3.13	2.16	1.83	1.56
C	5.32	2.78	2.21	2.92	2.49	1.82	1.49	1.22
D	6.34	3.57	2.88	3.22	3.00	1.98	1.62	1.19
E	6.32	3.57	2.93	3.27	3.03	2.07	1.63	1.36
								4,000
								1.77
								1.90
								1.43
								1.43
								1.59

Present Value of Fuels Used in 1985
\$/10⁶Btu(1)

Region	Coal		Natural Gas	
		Oil		
A	1.00	3.23	5.88	
B	0.30	3.84	2.52	
C	1.08	3.09	2.70	
D	1.07	2.94	1.92	
E	1.32	3.19	4.38	

1. Multiply values by 0.95 to obtain \$/GJ.

to 7. Indeed, in those cases, the cost of sludge disposal through energy crops could be eliminated through the sale of the energy crops.

- f. For all regions and all sizes of cities, the cost of disposal of sludge through energy crops or through agricultural crops is significantly lower than that for disposal through land-filling (compare items 6a and 6b with items 5b and 5c in the tables). Cost of disposal through energy crops does not include energy production costs or revenues from energy crops.
- g. For all regions and for cities with populations larger than about 50,000, the disposal cost for agricultural crops is lower than that for incineration if the equipment required to pretreat the sludge before land disposal is already in place and part of the wastewater treatment operation (compare items 6a and 6b with item 5b in the tables). If, however, a pre-treatment step must be installed and operated as part of the process of sludge disposal on land, the agricultural or energy crop method becomes competitive economically with incineration for cities with populations larger than about 700,000 (compare item 5b with items 6a or 6b plus item 9).
- h. For all regions and all sizes of cities, sludge disposal through the production of a woody energy crop results in reduced sludge disposal costs when compared with the alternative method of landfilling (item 7b in the tables). In most cases, the cost of disposal through an energy crop is only about 50% of the cost of disposal (operation and maintenance) by land-filling.
- i. For all regions and cities with populations larger than about 50,000, the use of sludge to produce woody energy crops results in reduced sludge disposal costs when compared with the alternative method of incineration if methods of sludge pretreatment for land disposal are in place and in operation (item 7a in the tables). In most cases, disposal through energy crops reduces sludge disposal costs about 50%. But if supplementary pretreatment must be constructed to permit land disposal through energy crops, disposal by incineration is more economical than disposal through energy crops for cities with populations up to about 700,000 (item 10 in the tables). For larger cities, replacement of incineration by disposal through an energy crop results in an annual saving of about 30% of the cost of disposal (operation and maintenance) by incineration.
- j. The economic advantage (if any) of the energy crop approach results from eliminating the cost of disposal (operation and maintenance costs) through the standard methods of disposal (incineration or landfilling).

- k. The cost of transporting the biomass back to the city where the sludge was generated does not significantly modify the results of Tables 3 to 7.
- l. The capital investment required to dispose of sludge through the energy crops is larger than the capital cost of the incinerator for large cities (\$38 million versus about \$4 million for cities of 4 million⁴) but much smaller than the cost of the incinerator for small cities (\$16,000 versus \$325,000--see Tables 3 through 7 and Reference 21) when no pretreatment equipment must be installed. In the case of large cities, the difference in capital cost is mostly due to the sludge transportation equipment (pipeline).
- m. The land areas required to dispose of the sludge at rates compatible with the nitrogen demand of the crop are small.

Further details concerning the economic analysis of the energy crop approach are given in Appendix D, Tables D-2 to D-6.

Electricity from Woody Energy Crops

Because of the high investment cost for small power plants, electricity production from woody crops is economically justified only for plantations of 6,070 to 8,094 ha (15,000 to 20,000 acres)--that is, for cities with populations of 2 million or more. The power plant computer model described in Appendix B was exercised for cities of 2 and 4 million located in Region C.

The results are presented in Table 9. An economic analysis of the electricity production from woody biomass is shown in Table 10 for the two cases considered in Table 9. The results of Table 10 show that for large population centers, electricity production from woody biomass is economically attractive. For the population center of 2 million, the net credit is smaller than when wood chips for fuel only are produced (see Table D-3), whereas for larger cities, the net credit is larger when electricity is produced. These conclusions will be strongly influenced, however, by the local price of electricity: In the northeastern part of the country, the situation will be more favorable than indicated in the table, and in areas where most electricity is supplied by hydroelectric plants, the situation will be less favorable for wood-fired power plants. As in the case of woody fuels, most of the net credit results from the elimination of the alternative methods of sludge disposal (incineration and landfill).

Fuel from Sugar Crops

As indicated in the last subsection of Section 4, ethanol can only be produced competitively from sugar crops in large conversion plants. With a 150-m³/day plant similar to those demonstrated in Brazil operating 330 days/year on 895 tons of silage corn per day, an area of about 5,000 ha (12,000 acres) would be required at a production rate of 56 metric tons/ha (25 tons/acre). At the recommended sludge application rates for Region C (about 25

TABLE 9
ELECTRICITY PRODUCTION FROM WOODY BIOMASS

Population	2,000,000	4,000,000
Biomass, ODMT/y ⁽¹⁾	77,246	154,492
(ODST/y) ⁽¹⁾	(85,167)	(170,333)
Plantation Area, Hectares	4,308	8,617
(Acres)	(10,646)	(21,292)
Cost of Biomass, \$/ODMT	23.2	27.2
(\$/ODST)	(21.0)	(24.7)
Generator Output, MW	17.6	35.2
Electricity Output, 10 ⁶ KWH/year	92.63	185.27
Load Factor	0.6	0.6
Investment, 10 ⁶ \$(2)	35.44	50.99
Annual Costs, 10 ⁶ \$/year ⁽³⁾	6.96	10.82
Product Cost, \$/KWH	0.075	0.058

(1) ODMT/y: oven-dry metric ton per year, ODST/y: oven-dry short ton per year. *year*

(2) Power plant only, not plantation operation.

(3) Includes cost of woody biomass fuel (taken from Table 5).

TABLE 10
ECONOMIC ANALYSIS OF ELECTRICITY PRODUCTION
FROM WOODY BIOMASS

Population	2,000,000	4,000,000
Incineration, 10^3 \$/year ⁽¹⁾	+2,606	+ 5,110
Landfill, 10^3 \$/year ⁽²⁾	+2,197	+ 4,088
Production Costs, 10^3 \$/year ⁽³⁾	-6,960	-10,820
Electricity Value, 10^3 \$/year	+5,558	+11,116
Net Dollar Balance		
Incineration	+1,204	+ 5,406
Landfill	+ 795	+ 4,384

+: Credit to energy crop operation; -: Cost to energy crop operation.

1. Cost of incineration if it was the chosen method of sludge disposal.
2. Cost of landfill if it was the chosen method of sludge disposal.
3. Electricity production cost. See Table 9.
4. Based on a present value of \$0.06 for electricity used in 1985 (see Table 2).

dry metric tons/ha·year), this would correspond to a population center of about 5 million. If the sugar crop is supplied only from sludge-treated land, the production of fuel from sugar crops is thus limited to a very small number of cases in the United States. The economic analysis for a population center of 5 million is shown in Table 11. The data in the tables show that if the experience with Brazilian ethanol plants can be confirmed in the United States, the production of ethanol from sludge-grown sugar crops is economically feasible for population centers of 5 million or more. A Battelle study³⁹ suggests, however, that ethanol production plants of at least 786 m³/day are required for ethanol from biomass to be competitive with ethanol produced from fossil fuels. If such is the case, ethanol from sugar crops can only be considered for a group of cities having a global population of about 26 million and located within a reasonable distance of each other. Few, if any, such cases exist. Another alternative is that the sugar crops produced by cities smaller than 5 million can be incorporated in the supply of a large ethanol plant relying on sources of sugar crops other than those grown from municipal sludge.

Fuels from Grain Crops

As indicated in Appendix A, a 786-m³/day, 330-day/year plant is considered the minimum size for the economic production of ethanol from grain crops. At the application rates quoted in Appendix A for climatic Region C (about 25 dry metric tons/ha·year), such a plant would absorb the sludge production of a population center of about 50 million. This situation does not exist in the United States. Another alternative is to feed the grain crop from sludge to a large plant relying on other sources of grain for its raw material supply.

Conclusions

The results presented in the previous paragraphs show that:

- a. Growing woody biomass for fuel on land used for sludge disposal is economically more advantageous than landfilling the sludge. Specifically, the energy crop approach reduces the cost of sludge disposal by about 50% in most cases.

This conclusion is valid for municipalities ranging in population from 10,000 to several million in climatic Regions C, D, and E. The same conclusion is valid for Regions A and B (California and the southwestern States) if species adapted to the climate (chaparral type, mesquite, or others) can be grown at a rate of about 11 dry metric tons/ha·year (5 dry tons/acre·year) under managed conditions with sludge applications.

- b. Growing woody biomass for fuel on land used for sludge disposal is economically more advantageous than incineration of sludge if land disposal does not require new pretreatment installations. Specifically, the energy crop approach reduces the cost of sludge disposal by about 50% in many cases.

TABLE 11
ECONOMIC ANALYSIS OF ETHANOL PRODUCTION FROM ENERGY CROPS
(REGION C)

Population:	5,000,000
Sludge: DMT/year ⁽¹⁾	115,869
(DST/year)	(127,750)
Incineration, 10 ³ \$/y ⁽²⁾	+16,224
Landfill, 10 ³ \$/y ⁽³⁾	+12,775
Area, Hectares ⁽⁴⁾	4,877
(Acres)	(12,052)
Biomass, MT/year ⁽⁵⁾	273,279
(ST/year)	(301,300)
Biomass production, 10 ³ \$/y ⁽⁶⁾	-3,281
Ethanol production, 10 ³ \$/y ⁽⁷⁾	-15,840
Market value of ethanol, 10 ³ \$/y ⁽⁸⁾	+18,810
Land and transportation costs ⁽⁹⁾ , 10 ³ \$/y	-2,621
Net Dollar Balance ⁽¹⁰⁾	
Incineration, 10 ³ \$/y	+19,194
Landfill, 10 ³ \$/y	+15,745

- +: Credit to energy crop operation; -: cost to energy crop operation.
1. DMT/y: dry metric ton per year; DST/y: dry short ton per year.
 2. Credit for elimination of incineration.
 3. Credit for elimination of landfill disposal of sludge.
 4. Area of plantation needed to feed a 150 m³/day ethanol plant, 330 day/year, at productivity of 56 metric tons/hectare·year (25 tons/acre·year) and sludge application rate of 24 metric tons/hectare·year (10.6 tons/acre·year).
 5. Biomass produced per year - MT: metric tons; ST: short ton.
 6. Cost of production of biomass (see Appendix A-10).
 7. Production cost of ethanol (\$0.32/liter). This cost includes biomass and land and sludge transportation costs, items (6) and (9).
 8. Present value of ethanol used in 1985 - \$0.38/liter.
 9. Land and sludge transportation costs for a distance of 160 km (100 miles).
 10. Sum of items (2) or (3), (7) and (8). A plus sign indicates that replacing incineration or landfill by ethanol production from biomass results in a credit for the sludge disposal operation, and vice versa for a minus sign.

This conclusion is valid for municipalities ranging in population from about 50,000 to several million in climatic Regions C, D, and E. The same conclusion is valid for Regions A and B (California and southwestern States) if species adapted to the climate (chaparral type, mesquite or others) can be grown at a rate of about 11 dry metric tons/ha·year (5 dry tons/acre·year) under managed conditions with sludge applications.

If supplemental pretreatment must be provided before disposal on energy crops, this approach is more competitive than incineration only for population centers larger than about 700,000. In that case, the energy crop approach reduces the cost of sludge disposal by about 36% of the cost required for incineration. The same conditions as above concerning species adapted to the climate apply for Regions A and B.

- c. Producing electricity from woody energy crops rather than producing wood chips for fuel is economically attractive for cities larger than about 2 million. The economic advantage to the sludge disposal operation may reach 50% or more of the cost of sludge disposal by incineration or landfilling for cities of about 4 million or more. The economic advantage varies locally with the market value of electricity in the region. The amount of electricity produced through sludge disposal for cities of 2 to 4 million is comparable with the sales of electricity of many rural or cooperative electric companies (15- to 25-MW range).
- d. Fuel (ethanol) production from sugar crops is only attractive for cities with populations larger than about 5 million if all the raw material is supplied from sludge-grown energy crops. The alternatives of grouping the sugar crops of several cities in the same geographical region or supplying a fraction of the raw material needed by a large ethanol plant is possible, but it has not been examined in detail.
- e. Fuel (ethanol) production from grain crops is only attractive for population centers of about 50 million if all the raw material is supplied from sludge-grown energy crops. The same alternatives as in item c above are open, but they are probably less attractive because of increased transportation costs.
- f. Between the two most attractive energy crop approaches (i.e., woody fuel and electricity from woody fuel), the required investment strongly favors the production of woody fuel.

ENERGY BALANCE

Another important factor that will determine the attractiveness of the energy-crop-from-sludge concept is the overall energy balance involved: Is the amount of energy generated by the crop and saved by eliminating other

methods of disposal larger than the amount of energy expended to produce the crop?

Woody Energy Crops for Fuel

A sample energy balance analysis for a city of 1 million is presented in Appendix D. The results are summarized in Table 12.

The overall energy credit is thus 36.8×10^9 to 41.6×10^9 joules/dry metric ton of sludge (31.7×10^6 to 36×10^6 Btu/dry ton of sludge). This credit results from a reduction of fossil fuel consumption of 3.5×10^9 to 8.6×10^9 joules/dry metric ton of sludge (3.1×10^6 to 7.4×10^6 Btu/dry ton of sludge) and the generation of 33.3×10^9 joules/dry metric ton of sludge (28.6×10^6 Btu/dry ton of sludge) of biomass fuel if sludge incineration is replaced by a sludge-grown crop. The replacement of landfilling by a sludge-grown energy crop results in a credit of 34.5×10^9 joules/dry metric ton of sludge (29.7×10^6 Btu/dry ton of sludge) because of a reduction of fossil fuel consumption of 1.3×10^9 joules/dry metric ton of sludge (1.1×10^6 Btu/dry ton of sludge) and the generation of 33.3×10^9 joules/dry metric ton of sludge (28.6×10^6 Btu/dry ton of sludge) of biomass fuel.

Electricity from Woody Biomass

For a city of 4 million (see electricity production data on Table 9), the energy credit resulting from the replacement of incineration by a woody biomass-from-sludge-fired power plant amounts to 10.8 to 15.8×10^9 joules/dry metric ton of sludge (9.3×10^6 to 13.6×10^6 Btu/dry ton of sludge). This credit results from a reduction of fossil fuel consumption of 3.6×10^9 to 8.6×10^9 joules/dry metric ton of sludge (3.1×10^6 to 7.4×10^6 Btu/dry ton of sludge) and the generation of 7.2×10^9 joules or 1.8×10^3 kWh/dry metric ton of sludge (6.2×10^6 Btu/dry ton of sludge) of electricity. In the case of landfilling, the credit is 8.5×10^9 joules/dry metric ton of sludge (7.3×10^6 Btu/dry ton of sludge) as a result of a reduction in fossil fuel consumption of 1.3×10^9 joules/dry metric ton of sludge (1.1×10^6 Btu/dry ton of sludge) and the generation of 7.2×10^9 joules or 1.8×10^3 kWh/dry metric ton of sludge (6.2×10^6 Btu or 1.8×10^3 kWh/dry ton of sludge) or electricity.

Fuels from Sugar and Grain Crops

The ratio of fuel produced from the energy crops to the fuel used in the crop generation has been estimated to be from 2 to 8. The credit for eliminating incineration or landfilling is added to this amount of energy produced and results in a net energy credit. In view of the limited potential of this approach, a detailed energy balance was not performed.

Agricultural Crops

Sludge disposal on agricultural crops rather than through incineration or landfilling results in the energy credits shown in Table 12 for the elimination of incineration or landfilling, but it does not create the energy crop energy credit. The energy used for producing the agricultural

TABLE 12
SUMMARY ENERGY BALANCE
 (Units: 10^9 Joules/Metric Ton)⁽¹⁾

	<u>Incineration</u>	<u>Landfilling</u>
Fossil Fuel Saved	4.4 - 9.2	2.1
Fuel Value of Energy Crops	33.3	33.3
Total Energy Credits	37.7 -42.5	35.4
Energy Used in Production of Energy Crops	0.87	0.87
Overall Energy Credit	36.8 -41.6	34.5

(1) 10^9 Joules/Metric Ton = 0.86 10^6 Btu/ton.

crops is comparable with the amount used to produce the energy crop. The net credits are thus 3.5 to 8.3×10^9 joules/metric ton and 1.2×10^9 joules/metric ton for the elimination of incineration and landfilling, respectively.

Conclusions

Of the two most attractive energy-crops-from-sludge approaches (i.e., woody fuel production and electricity generation from woody crops), the production of woody fuel results in a much higher overall energy credit per unit of sludge processed. Disposal of sludge on energy crops results in a much higher energy credit than disposal on agricultural crops.

SENSITIVITY ANALYSIS

As indicated in Section 4, some of the components of the cost and energy analysis presented earlier in this section may vary significantly with respect to the average values quoted in Appendix A. Specifically, the cost of incineration and landfill, particularly for small treatment plants, may be lower than the values shown in Figure 4. This variation could have a drastic effect on the economic feasibility of the concept, as the credit received for eliminating these operations is the major element making the energy crop approach economically attractive. Another uncertainty is the biomass yields, particularly in Regions A and B (California and the Southwest), for which yields of 11 dry metric tons/ha-year (5 dry tons/acre-year) from managed desert-shrubs plantations have been assumed. Significant variations in productivity could also be recorded in the other three climatic regions, particularly as marginal land is intended for sludge disposal. Uncertainty also exists for the energy crop production costs: As indicated in Appendix A, production costs could be boosted by about 20% if special precautions must be taken during the application of sludge to the plantation. The sludge transportation and land costs may be higher than quoted, particularly for large cities, if the minimum distance at which plantation land can be found is greater than the optimum distance of 160 km (100 miles - see case of Chicago, for instance). Finally, in the case of electricity generation from woody crops, the market value of electricity may be lower than the average value used in the economic estimate.

A wide range of values for the amount of auxiliary fossil fuel required for incineration is quoted (see Table 12). But this situation does not affect the overall positive energy balance resulting from the implementation of the energy crop approach.

The sensitivity of the economic and energy balance analysis to the above-mentioned factors is examined for the cases of a small (population 10,000) city and a large (population 4 million) city. Except for the biomass yield, the analysis is performed for cities in Region C.

Sensitivity to Variations in Incineration and Landfill Costs

Results of the analysis are shown in Table 13. It is apparent that decreasing by half the credit taken for elimination of incineration reduces the overall dollar credit by about 100% when no supplemental pretreatment is needed.

If supplemental pretreatment is needed before sludge application to energy crops, a credit decrease of 50% for eliminating incineration would make disposal through energy crops economically unattractive. Decreasing by half the credit for landfilling eliminates the economic advantage of the energy crop approach. As indicated in Figure 4, variations in credits of the order considered above could occur, particularly for small cities; thus definite conclusions on the economic advantage of the energy crop approach must be evaluated on a case-by-case basis.

The analysis assumed that the credit for eliminating landfilling amounts to the operation and maintenance costs of the landfilling operation and that the capital retirement costs for the landfilling operation are still incurred by the municipality. In some cases, however, some of the equipment previously used for landfilling could be used for the energy crop method of disposal. In those cases, the debt retirement cost corresponding to this reusable equipment would also become a credit for the municipality switching from landfilling to energy crop disposal. Such cases can only be analyzed on a case-by-case basis.

Sensitivity to Biomass Yields

It was assumed that biomass yields of 11 dry metric tons/ha-year (5 dry tons/acre-year) can be obtained from managed, sludge-fertilized plantations of desert shrubs or other species adapted to the climate of Regions A and B (California and the southwestern States). A decrease in yield of 50% was assumed: The resulting annual yield is close to that observed in unmanaged stands of chaparral⁵² and is thus certainly achievable. Decreasing the yield will affect proportionally the plantation area and thus the land costs required to dispose of the sludge as well as the transportation (and associated fuel consumption) costs within the plantation area. The effect is mostly felt for large population centers for which the cost of land at a reasonable distance from the city is significantly higher than for small cities (see Appendix A). The effect on the energy balance is negligible.

In other regions of the country (C, D, and E), yields of about 8 oven-dry tons/acre-year were assumed. Though such yields have been demonstrated in short-rotation experimental plantations, variations in local climate, rainfall, and soils will result in lower yields in many instances. A decreased yield of 50% was assumed. Under those conditions, the economic advantage of the energy crop approach is drastically decreased but not completely eliminated.

TABLE 13
SENSITIVITY ANALYSIS

Population (10 ³)	10	4,000	10	4,000	10	4,000
	Percent Change ⁽¹⁾		Percent Change of ⁽²⁾		Percent Change of ⁽³⁾	
Variable	%		%		%	
1. Cost of Incineration						
a. No pretreatment required	*	-50		-99	-	-
b. Supplemental pre-treatment required	*	-50		-128	-	-
2. Cost of Landfill	-50	-50	-100	-130	-	-
3. Biomass Yields						
Region A-Incineration						
a. No pretreatment	*	-50		-88	~1	
b. Supplemental pre-treatment	*	-50		-124	~1.5	
Landfill	-50	-50	-7	-148	~1	
Region B-Incineration						
a. No pretreatment	*	-50	*	-110	~1	
b. Supplemental pre-treatment	*	-50	*	-152	~1.5	
Landfill	-50	-50	-4	-113	~1	
Regions C,D,E						
Incineration						
a. No pretreatment	*	-50	*	-57	~1	
b. Supplemental pre-treatment	*	-50	*	-71	~1.5	
Landfill	-50	-50	-5	-86	~1	

TABLE 13 (continued)

Population (10 ³)	10	4,000	10	4,000	10	4,000
	Percent Change ⁽¹⁾		Percent Change of ⁽²⁾		Percent Change of ⁽³⁾	
Variable	<u>%</u>		<u>%</u>		<u>%</u>	
4. Biomass Production						
Cost						
Incineration						
a. No pretreatment	*	+20	*	-67	-	-
b. Supplemental pre-treatment	*	+20	*	-84	-	-
Landfill	+20	+20	-14	-64	-	-
5. Distance from City to Plantation						
Incineration						
a. No pretreatment	*	+100	*	-11	~1.6	
b. Supplemental pre-treatment	*	+100	*	-14	~1.6	
Landfill	+100	+100	-10	-15	~1.7	
6. Cost of Electricity						
Incineration						
a. No pretreatment	*	-50	*	-130	-	-
b. Supplemental pre-treatment	*	-50	*	-163	-	-
Landfill	**	-50	**	-171	-	-

Notes to Table 13

1. Percent change of the cost of incineration (credit) used in Table 3.
 2. Percent change of the net dollar balance estimated in Table 3 (Item 10).
 3. Percent change of the energy balance discussed in Sections VI-B-2.
- * Sludge disposal by incineration is generally not practiced for population centers of less than about 50,000 people (see reference 74). The sensitivity analysis was thus not performed in the cases marked by an asterisk.
- ** The generation of electricity from woody energy crops only applies for population centers larger than about 2,000,000 people.

Sensitivity to Biomass Production Costs

Because of special precautions such as contour planting, terrace work, etc. that may be required to prevent runoff or other detrimental effects related to the periodic application of sludge to the land, the production costs of biomass could be about 20% higher than those used in Table 5. As shown in Table 13, this variation would have a significant effect on the economics of the energy crop approach.

Sensitivity to Distance from the Sludge-Generating City to the Energy Crop Plantation

The distances from city to plantation that are used in Table 5 are either the minimum distance at which sufficient land is found for energy crop plantations (cities with populations up to about 700,000) or the distance for which the combined land and sludge transportation costs are minimum. As is the case for Chicago (for which this figure is 200 miles), plantations may have to be located farther from the city than the distance ensuring minimum combined costs. The combined effects of lower land costs and higher sludge transportation costs that occur as distance increases from the city have little effect on either the economics or the energy balance of the energy crop approach.

Sensitivity to the Cost of Electricity

When the product generated from woody crops is electricity, the market value for that product largely determines the economic feasibility of the energy crop concept. This is reflected by the fact that a decrease of 50% in the sale price of electricity on the local market eliminates completely the economic advantage of the energy crop approach.

Conclusions

The above analysis thus indicates that the economic advantage of the energy crop approach over sludge disposal through incineration or landfilling is extremely sensitive to (a) the value of the credits used in the analysis, (b) the yields of the energy crop, and (c) the market value of electricity if the latter is the end product generated from the energy crop. Specifically, variations of credit values, biomass yields, and market values of electricity within the range that can be expected for these quantities will, in most cases, eliminate the economic advantage of the energy crop approach over incineration or landfilling. Variations in biomass production costs or in the distance from the city to the plantation have smaller impacts on the economic position of the energy crop approach compared with incineration or landfilling. The impact of variations in credits, yields, production costs, distance of transportation, and cost of electricity on the positive energy balance resulting from the energy crop approach is negligible.

The sensitivity analysis thus shows that great caution must be exercised when comparing the economics of sludge disposal through energy crops with those of incineration or landfilling. Case studies are required to draw definitive conclusions.

The analysis also confirms that the energy crop approach results in a positive energy balance.

POTENTIAL IMPACT OF THE ENERGY-CROP-FROM-SLUDGE APPROACH ON A NATIONAL SCALE

The preceding subsections have shown that growing energy crops on land used for sludge disposal can be economically attractive and can result in a net energy credit for cities with populations of 10,000 to several million. In view of the high sensitivity to local factors of the relative economic value of the energy crop approach as compared with incineration or land-filling, it would be meaningless at this point to evaluate the impact of the energy crop approach on a national scale.

ENVIRONMENTAL AND SOCIAL ASPECTS

The disposal of sludge through the growth of energy crops is attractive from an environmental point of view: It generates perpetually renewable energy of low sulfur content, and it does not affect the carbon dioxide balance in the atmosphere. As shown in Appendix C, the rates of sludge application on woody crops are compatible with the limitations presently imposed when disposing of sludge on agricultural land. Thus the land used for energy crop production could be returned to agricultural production at a later time. Also, this approach puts back to use areas of land that are abandoned or neglected.

Sludge disposal on energy crops is a source of permanent employment, particularly in rural areas where the energy crop plantations are operated. A detailed balance between the number of jobs lost through elimination of incineration and landfilling and the number of jobs created through the energy crop plantation has not been performed.

APPENDIX A

DATA BASE

DISTRIBUTION AND ANNUAL PRODUCTION OF MUNICIPAL SLUDGES

The quantity of municipal wastewater treatment sludge varies both with the size of the treatment plant and type of treatment being used at that plant. A primary treatment plant, which consists of sedimentation of settleable solids, produces approximately 120 kg/day of solids in the primary sludge for every million liters (or thousand cubic meters) per day of influent wastewater treated (1,000 lb/day of solids in the primary sludge for every MGD of influent wastewater treated). This sludge is approximately 5% solids. The quantity of solids from a secondary treatment plant ranges from 50% to 100% higher than that of the primary plant alone.⁴ This includes the 120 kg/day per thousand cubic meters (1,000 lb/day per MGD) of primary sludge plus sludge from the biological system. Secondary sludge is primarily biomass and is very dilute (on the order of 1% solids or less). Plants that involve tertiary treatment will produce chemical sludges with double the daily solids production per cubic meter or per MGD of a secondary plant. At present, only a small number of municipal plants use tertiary systems.

According to U.S. Environmental Protection Agency (EPA) data, approximately 22,000 wastewater treatment plants existed in the United States in 1974 serving a sewered population of approximately 155 million. These plants produced approximately 4.5 million metric tons (5 million short tons)/year of sludge solids.^{4,5} A breakdown of the number and type of municipal wastewater treatment plants appears in Table A-1. Table A-2 contains a State-by-State summary of sewered population and the sludge solids produced by the treatment plants in that State.

COMPOSITION OF MUNICIPAL SLUDGE

The treatment of municipal wastewater involves the separation of pollutants from the wastewater stream. The pollutants that have been removed are concentrated into an easily handled form for disposal. The amount and physical, chemical, and biological characteristics of the sludge are affected by the degree of treatment, the chemicals added, and the type and composition of the municipal wastewater influent.

Because of odor and pathogen problems, raw sludges must be treated before ultimate disposal. The most common sludge treatment methods include heat treatment, aerobic and anaerobic digestion, chemical and physical

TABLE A-1
THE NUMBER AND TYPE OF MUNICIPAL
WASTEWATER TREATMENT FACILITIES IN
THE UNITED STATES AND POPULATION SERVED BY EACH*

<u>Type of Treatment Process</u>	<u>Population Served</u>	<u>Number of Plants</u>
Collection System Only - No Treatment	2,890,676	2,404
Minor Treatment - Screening and Chlorination Only	780,135	72
Primary Treatment - Sedimentation	37,904,943	2,714
Intermediate Treatment - Chemical	6,780,241	70
Secondary Treatment - Biological	2,506,245	1,980
Secondary - Activated Sludge	47,561,508	1,831
Secondary - Extended Aeration	3,963,602	2,694
Secondary - Trickling Filter	29,688,917	3,523
Secondary - Effluent to Land	410,444	144
Secondary - Oxidation Pond	7,680,982	5,031
Secondary - Filter	1,606,110	309
Secondary - Miscellaneous	10,798,203	1,245
Tertiary - Physical, Chemical	2,373,698	809
Total	154,945,105	22,054

* U.S. Environmental Protection Agency, Office of Water Programs.
 Unpublished Data, 1974.

TABLE A-2 - 1974 SEWAGE SLUDGE GENERATION (DRY)

	Cat. I (1) Population (10 ³)	Cat. I (1) Sludge (Tons) (3)	Cat. II (2) Population (10 ³)	Cat. II (2) Sludge (Tons) (3)	Sludge Total (Tons) (3)
Totals					
1. Alabama	622	13,684	1,101	46,242	59,926
2. Alaska	143	3,146	30	1,260	4,406
3. Arizona	-	-	1,626	68,292	68,292
4. Arkansas	157	3,454	755	31,710	35,164
5. California	7,755	170,610	10,538	442,595	613,296
6. Colorado	18	396	2,314	97,188	97,584
7. Connecticut	976	21,472	968	40,698	62,170
8. Delaware	19	418	442	18,564	18,982
9. District of Columbia	-	-	1,780	74,760	74,760
10. Florida	584	12,848	3,091	129,822	142,670
11. Georgia	959	21,098	1,363	57,246	78,344
12. Hawaii	116	2,552	206	8,652	11,204
13. Idaho	158	3,476	266	11,130	14,606
14. Illinois	669	14,718	8,362	351,204	365,922
15. Indiana	321	7,062	3,077	129,234	136,296
16. Iowa	334	7,348	1,424	54,808	67,156
17. Kansas	227	6,994	1,534	64,428	69,422
18. Kentucky	672	14,784	813	34,146	48,930
19. Louisiana	684	15,408	1,016	42,672	58,080
20. Maine	80	1,760	111	4,662	6,422

(continued)

TABLE A-2 - 1974 SEWAGE SLUDGE GENERATION (DRY) (Cont'd)

	Cat. I (1) Population (10 ³)	Cat. I (1) Sludge (Tons) (3)	Cat. II (2) Population (10 ³)	Cat. II (2) Sludge (Tons) (3)	Sludge Total (Tons) (3)
<u>Totals</u>					
21. Maryland	344	7,568	2,237	93,954	101,522
22. Massachusetts	2,557	56,254	952	39,984	96,238
23. Michigan	3,214	70,708	2,271	96,382	166,090
24. Minnesota	228	5,016	1,601	67,242	72,258
25. Mississippi	4	88	991	41,622	41,710
26. Missouri	2,667	58,674	1,413	59,346	118,020
27. Montana	163	3,586	268	11,256	14,842
28. Nebraska	292	6,424	942	39,564	45,988
29. Nevada	5	110	509	21,378	21,488
30. New Hampshire	171	3,762	64	2,688	6,450
31. New Jersey	3,306	72,732	3,072	129,024	151,756
32. New Mexico	1	22	884	37,128	37,150
33. New York	4,130	90,860	9,737	408,954	499,814
34. North Carolina	43	946	2,269	95,298	96,244
35. North Dakota	8	176	389	16,338	16,514
36. Ohio	676	14,872	8,146	342,132	357,004
37. Oklahoma	168	3,696	1,634	68,628	72,324
38. Oregon	597	13,134	980	41,160	52,294
29. Pennsylvania	1,205	26,510	11,649	489,258	515,768
40. Rhode Island	110	2,420	602	25,284	27,704

(continued)

TABLE A-2 - 1974 SEWAGE SLUDGE GENERATION (DRY) (Cont'd)

	Cat. I (1) Population (10 ³)	Cat. I (1) Sludge (Tons) (3)	Cat. II (2) Population (10 ³)	Cat. II (2) Sludge (Tons) (3)	Sludge Total (Tons) (3)
Totals					
41. South Carolina	215	4,730	1,125	47,250	51,980
42. South Dakota	47	1,034	369	15,498	16,537
43. Tennessee	79	1,738	1,512	63,504	65,242
44. Texas	108	2,376	11,050	464,100	466,476
45. Utah	13	286	972	40,824	41,110
46. Vermont	154	3,388	75	3,150	6,538
47. Virginia	977	21,494	2,003	84,126	105,620
48. Washington	1,444	31,768	833	34,986	66,754
49. West Virginia	373	8,206	356	14,952	23,158
50. Wisconsin	503	11,066	2,710	113,820	124,886
51. Wyoming	47	1,034	244	10,248	11,282
52. Guam					
53. Puerto Rico					
54. Virgin Islands	38,343	843,596	112,676	4,732,392	5,575,938

(1) Category 1 Treatment Plant: plants with minor treatment, primary treatment or intermediate treatment.

(2) Category 2 Treatment Plant: plants with secondary or tertiary treatment.

(3) Tons = short tons = 0.91 metric tons.

Source: Reference 4.

dewatering, and incineration. Each of these procedures results in a final sludge with different solids content, organic content, and chemical composition.⁷

To develop a typical sludge composition for use in this study, several simplifying assumptions had to be made. This study is directed toward planning the near future. Consequently, sludge characteristics were selected that reflect the most likely situation in the year 1985. The present assumption is that most municipal plants will meet secondary treatment standards--treatment for removal of BOD₅ (five-day biological oxygen demand) and suspended solids.

Such pretreatment might eliminate much of the heavy metals problem now facing municipal waste treatment plants, and for this study, it was assumed. The sludges from industrial pretreatment and from municipal tertiary treatment plants might be unacceptable for land spreading because of the high chemical concentration. The vast majority of municipal plants, however, will be producing a usable combined sludge, the results of both primary and secondary treatment.

The major parameters that are of concern in typifying municipal sludges are: solids content, nutrient content, persistent organics content, and heavy metals content. Even among secondary treatment plants it is obvious that concentrations of components vary widely.^{8,9,10,11} Table A-3 illustrates this variability.¹² Because the distribution is so skewed, Sommers suggests the use of the median value as opposed to the mean values.¹⁰ The results for digested sludges appear in Table A-4. The values for nutrients are 20% lower because of the inclusion of tertiary sludges in the average values. Sludges typically come out of the digester at about 4% solids. It is important to remember that the compositions depend greatly on whether or not the sludges are dewatered. Virtually all the potassium in the sludge is in the liquid phase. More than half of the nitrogen and phosphorus are in the organic and solid states.¹¹ Consequently, any dewatering after digestion will have a dramatic effect on the nutrient value of the sludge. Dewatering does allow, however, for increased application rates per hectare (acre) to match the nutrient composition of wet sludge. The ratio of fertilizer value of dewatered sludge to commercial fertilizer is approximately 1:5.⁹ It is most deficient in potassium, the element most eliminated through dewatering.

COST OF ULTIMATE DISPOSAL OF MUNICIPAL SLUDGE

Costs of processing waste treatment sludge in sewage treatment plants often account for at least 40% of the total costs of operation. Cost accounting of sludge operations must include all processing and handling, from the actual generation of the sludge through ultimate disposal. This accounting should include sludge thickening after its removal from both primary and secondary clarifiers. Heat treatment, digestion, dewatering, land spreading, and incineration are just a few of the options available for sludge management. A number of studies in the literature (primarily funded by EPA) deal with the cost of sludge disposal.^{13,14,15,16,17,18} The studies differ on baseline assumptions, making them hard to compare. Differences in the rate

TABLE A-3
RANGE OF CONCENTRATION OF VARIOUS CONSTITUENTS IN
ANAEROBIC LIQUID DIGESTED SLUDGE FROM 35 WISCONSIN MUNICIPALITIES

<u>Constituent</u>	<u>Range*</u>	
	%	
Total-N (moist)	3.4	9.5
Total-N (dried)	2.4	3.1
NH ₄ -N (moist)	0.8	4.1
NH ₄ -N (dried)	0.02	0.26
Organic C	25.7	38.5
P	2.7	6.1
K	1.2	1.9
Ca	4.2	18.0
Mg	0.8	1.2
Na	0.6	2.2
Al	0.36	1.2
Fe	0.8	7.8
Cd/Zn	0.15	33
	mg/kg	
Zn	490	12,200
Cu	140	10,000
Ni	15	1,700
Cd	5	400
Pb	40	4,600
Cr	50	32,000
Hg	0.6	31
B	150	750
Mn	180	1,130
Ba	530	1,340
Sr	52	7,810

*Range for the first 13 constituents is given in % of solids and in mg/kg for the last 11 constituents.

Source: Reference 12.

TABLE A-4
MEDIAN CONCENTRATIONS OF MAJOR CONSTITUENTS
IN SEWAGE SLUDGE

<u>Component</u>	<u>Type of Sludge</u> <u>Anaerobic</u>	<u>Anaerobic</u>
	%	
N	4.2	4.8
P	3.0	2.7
K	0.3	0.4
Na	0.7	0.8
Ca	4.9	3.0
Mg	0.5	0.4
Fe	1.2	1.0
Al	0.5	0.4
	mg/kg	
Pb	540	300
Zn	1,890	1,800
Cu	1,000	970
Ni	85	31
Cd	16	16
Cr	1,350	260

Source: Reference 10.

of sludge generation per MGD, in financing rates, and in financing procedures all have dramatic effects on the final cost per dry ton of sludge handling. Also, little agreement exists on such basic points as what a dry ton of solid represents. In some studies, it represents the sludge actually generated in the primary and secondary wastewater treatment operations; in other, it represents sludge actually going to ultimate disposal.

The operation and maintenance treatment costs can be broken down into three basic areas: (1) the sludge processing at the treatment plant, which usually involves some kind of sludge stabilization, (2) sludge transportation to the disposal site, and (3) application or deposition of the sludge at the ultimate disposal site. The major ultimate disposal methods currently being used or under investigation include the following: Composting, incineration, landfill of dewatered sludge, ocean disposal, and land spreading. Selection of the ultimate disposal method is not limited to a least-cost consideration.

The cost and applicability of each method varies most widely with the given locale. For example, incineration may be restricted because of lack of available supplementary fuel or because of restrictive air pollution codes. Ocean disposal is clearly limited to coastal cities and will, in the future, be eliminated because of long-range effects on the ocean ecosystem. Land spreading and landfill operations are controlled by the availability of land near the urban center. In each case, transportation is a major sludge disposal cost.

Each municipality will have to face its own energy balances and cost tradeoffs in selecting the optimum combination of sludge treatment, transportation, and disposal. Important factors include climate, municipal financing procedures, volume of sludge to be dealt with, air pollution restrictions, land availability, and terrain. The predominant influence is the quantity of sludge. At present, the larger treatment plants are more likely to use either ocean disposal or incineration. Smaller plants tend to favor land spreading, sale or give-away of sludge, or composting and subsequent distribution of the compost. A breakdown of the treatment plants in the United States shows that as of 1975, the ocean dumping method was used for 15% of the municipal sludge. Incineration counted for 35%, with landfill and spreading each accounting for another 25%. Typical data for the various methods of sludge handling are shown in Table A-5.

Table A-6 shows the analysis done for the City of Chicago: a variety of sludge disposal options were evaluated, and land spreading evolved as the least expensive treatment method in this case--despite 320-km (200-mile) transport to the disposal site in southern Illinois. Similar data were developed for a subsurface injection system.¹⁹ These data show the actual application cost to be less than 20% of the total sludge handling cost.

Comparison of energy cropland disposal will be made with data developed from a recent EPA publication entitled "Wastewater Sludge Utilization and Disposal Costs."¹³ This study supplies costs for several different disposal methods. The two competing with land spreading include (a) vacuum filtration, incineration, transportation and landfill of the resulting ash (alternative I on Figure A-1), and (b) dewatering of digested sludge, transportation, and

TABLE A-5
CURRENT DISPOSAL AND UTILIZATION OF MUNICIPAL SLUDGE

Ocean Dumping	15%
Incineration	35%
Landfill	25%
Landspreading	25%
Crops	20%
Other	05%

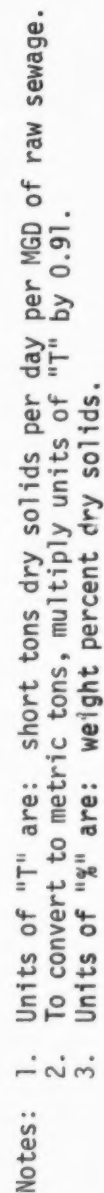
Source: Reference 1.

TABLE A-6
METROPOLITAN SANITARY DISTRICT OF GREATER CHICAGO:
ESTIMATED COSTS FOR SLUDGE DISPOSAL

<u>Method</u>	<u>Cost¹-\$/dry metric ton</u> <u>(\$/dry short ton)</u>
Drying and Sale as Fertilizer	
Gross	115
	(105)
Net	86
Wet Air Oxidation (Zimpro) ²	96
	(87)
Dewatering and Incineration ²	110
	(100)
Digestion and Permanent Lagoons	94
	(86)
Digestion and Reclamation on	58
Farm Lands	(52)
Digestion and Reclamation on	58
Strip Mines	(52)

(1) 1977 dollars.

(2) Preceded by high-rate digestion.



landfill of the dewatered sludge (alternative V on Figure A-1). Alternatives II and III (Figure A-1), which result in ocean dumping, are not considered in the comparison, as this method of ultimate disposal must be eliminated by 1985. A third alternative--transportation and landspreading of digested sludge but without credit for the nutrient value of the sludge--is also included for comparison purposes (alternative IV on Figure A-1).

Assessment of the application of municipal sludge on energy crops assumes that at one point in time, the method of sludge disposal presently used--incineration or landfiling--is replaced by disposal on energy crops. After this replacement, the operation and maintenance costs for the original (in-place) system become a credit to the municipality. The capital cost or debt retirement costs for the in-place system, however, will still be incurred until the debt for the in-place system is fully retired. Operation and maintenance costs for in-place systems for a variety of treatment plant sizes were derived from References 20, 21, 72, 73, 74, and 75. The data are presented in Table A-7.

No costs are quoted for incineration and landfiling for municipalities with populations smaller than 50,000; the data from reference 72 show that few (two cases only) municipalities of that size used this method for the disposal of sludge in the 1973-77 period. Comparison of disposal on energy crops with other disposal methods will thus not include incineration for municipalities smaller than 50,000.

The data are plotted on Figure A-2. Also plotted on the figure are individual data points for actual case studies.⁷⁵ For cities with populations larger than 100,000, the agreement between the calculated curves and the experimental points is fairly good, although wide variations in treatment costs are recorded among the experimental points. For cities smaller than 100,000, and particularly for cities smaller than 50,000, the discrepancy between the calculated costs of disposal (curves) and the actual data points is generally large. Except for the incineration costs, which are higher than calculated (points 1 and 14 on the figure), most actual disposal costs are significantly lower than those predicted from the cost curves. These wide differences are probably due to local factors such as land costs and hauling distance/costs, which may be quite different from those assumed to generate the general cost curves on the figure. A sensitivity analysis will be performed to evaluate the impact of these wide variations in disposal costs.

The curve showing the cost of sludge disposal via energy crops is also shown on the figure and anticipates the results of the analysis.

Most incinerators of the pre-1973 period burned sludge with a solids content in the 15 to 30% range. Increasing solids to 35 to 40 wt % with a volatile solids content larger than or equal to 60% makes incineration more economically competitive with other disposal methods. Jones et al. claim that with increased solids content, this process will be competitive even when fuel prices double.²² This potential improvement of incinerator performance will be acknowledged by performing a sensitivity analysis to estimate the impact of reduced incineration costs on the economic assessment of sludge disposal on energy crops as compared with disposal by incineration.

TABLE A-7: COST OF DISPOSAL OF SLUDGE
(OPERATION AND MAINTENANCE COSTS - 1977 DOLLARS)

Population	Yearly Sludge Produced ¹		Incineration ² Landfill		Dewatering ³ Landfill		Landspreading ⁴	
	DMT/y ⁵	(DST/y) ⁶	\$/DMT ⁷	(\$/DST) ⁸	\$/DMT ⁷	(\$/DST) ⁸	\$/DMT ⁷	(\$/DST) ⁸
10,000	237	(260)	-	-	262	(238)	167	(152)
25,000	582	(640)	-	-	176	(160)	162	(147)
50,000	1,170	(1,280)	88	(80)	132	(120)	147	(134)
100,000	2,370	(2,600)	71	(65)	101	(92)	117	(106)
200,000	4,640	(5,100)	64	(58)	80	(73)	85	(77)
350,000	8,100	(8,900)	57	(52)	68	(62)	67	(61)
700,000	16,300	(17,900)	56	(51)	57	(52)	52	(47)
2,000,000	46,500	(51,100)	55	(50)	47	(43)	37	(34)
4,000,000	92,800	(102,000)	55	(50)	43	(39)	31	(28)
7,000,000	164,000	(180,000)	54	(49)	42	(38)	27	(25)

Source: Timothy G. Shea and John D. Stockton - Wastewater Sludge Utilization and Disposal Costs - Technical Report EPA-430/9-75-015, September 1975, MCD-12. U.S. Environmental Protection Agency - A Guide to the Selection of Cost-Effective Wastewater Treatment Systems - Technical Report - EPA-430/9-75-002, July 1975. U.S. Environmental Protection Agency - An Analysis of Construction Cost Experience for Waste Water Treatment Plants - EPA-430/9-76-002, February 1976.

(1) Based on 0.064 kg/capita-day (0.14 lb/capita-day).

(2) Vacuum filtration, incineration, truck transportation and landfilling.

(3) Dewatering of sludge, truck or rail transportation and landfilling.

(4) Pipeline or truck transportation, landspreading, no credit for nutrient value of sludge.

(5) Dry metric tons/year.

(6) Dry short tons/year.

(7) July 1977 dollars/dry metric ton.

(8) July 1977 dollars/dry short ton.

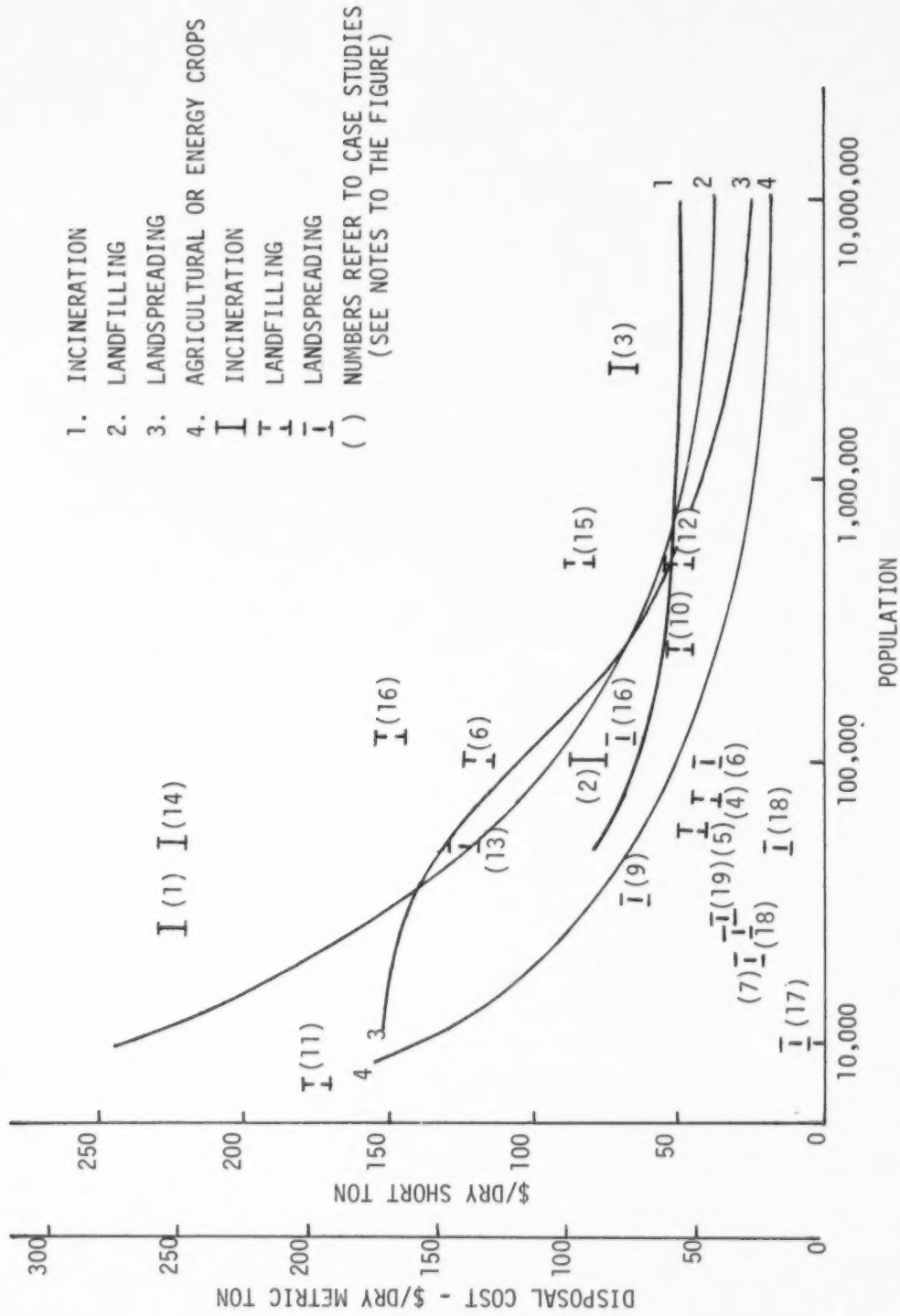


Figure A-2. Cost of sludge disposal (operation and maintenance costs, 1977 dollars). See notes on following page.

Notes to Figure A-2

Source: Curves: Timothy G. Shea and John D. Stockton - Wastewater Sludge Utilization and Disposal Costs - Technical Report EPA-430/9-75-015, September 1975, MCD-12; U.S. Environmental Protection Agency - A Guide to the Selection of Cost-Effective Wastewater Treatment Systems - Technical Report - EPA-430/9-75-002, July 1975; U.S. Environmental Protection Agency - An Analysis of Construction Cost Experience for Wastewater Treatment Plants - EPA-430/9-76-002, February 1976.

Charles E. Pound, Ronald W. Crites and Douglas A. Griffes, Cost of Wastewater Treatment by Land Application, Technical Report EPA-430/9-75-003, June 1975.

Points

- (1) Mr. Bruce McDaniel - Sanitary Board - Clarksburg, W. Va. - Estimated cost for incineration and disposal.
- (2) (3) Jerry L. Jones, David C. Bomburger Jr., F. Michael Lewis and Joel Jacknow - Municipal Sludge Disposal Economics - Environmental Science and Technology, 11, No. 10, Oct. 1977 - Estimated costs for incineration and landfill.
- (4) and over: R. Kent Anderson, Cost of Landspreading and Hauling Sludge from Municipal Wastewater Treatment Plants - Case Studies, EPA/530/SW-619, October 1977. The numbers on Figure A-2 refer to the following cities:
 - (4) Anderson, Indiana.
 - (5) Appleton, Wisconsin.
 - (6) Bethlehem, Pennsylvania.
 - (7) Collinsville, Illinois.
 - (8) Danville, Virginia.
 - (9) Ft. Pierce, Florida.
 - (10) Grand Rapids, Michigan.
 - (11) Lawrenceville, Illinois.
 - (12) Louisville, Kentucky.
 - (13) Sheboygan, Wisconsin.
 - (14) Sheboygan, Wisconsin, cost for vacuum filtration and residual disposal excluding incineration.
 - (15) Toledo, Ohio.
 - (16) York, Pennsylvania.
 - (17) Front Royal, Virginia.
 - (18) Beavercreek Township, Greene County, Ohio.
 - (19) Lebanon, Pennsylvania.

Note: Two data points are plotted for some cities when data for both landfilling and landspreading disposal have been generated.

The costs quoted in Table A-7 represent the credit to the municipality that results from converting from standard sludge disposal methods to land-spreading for energy crop production. These values will be used as the basis for evaluating the cost of sludge disposal. The fact that these costs may fluctuate significantly, particularly for small municipalities, must be acknowledged, however.

SLUDGE TRANSPORTATION COSTS

The total annual cost attributable to sludge handling may be broken into three distinct segments: (1) sludge stabilization at the wastewater treatment plant, (2) sludge transportation to the disposal site, and (3) ultimate disposal. Sludge transportation has been identified as a major cost in all sludge handling schemes, and in small treatment plants, it represents approximately half the total sludge handling cost.¹⁹ The fraction of sludge handling cost associated with transportation decreases with increasing size of the plant and with the use of more sophisticated dewatering and solids reduction techniques. These include digestion, filtration, and incineration.⁷

Four major methods exist for transporting municipal sludges. These include fixed pipelines, barges, tank trucks, and rail tank cars. Tank trucks and rail transportation may be used for hauling either liquid or dewatered sludges, and pipeline and barge transportation are limited to liquid sludges. Table A-8 describes the various transportation methods and makes comments on their applicability for sludge transport. More specific information is available in the literature and from equipment vendors.^{19,22}

Selecting the optimum method of sludge transport depends on many factors; the final determination is based on the lowest cost of sludge handling to the municipality. The factors influencing this bottom-line cost include the capital and operating and maintenance O & M costs associated with each method, and the financing procedures of the individual municipality. One of the overriding factors influencing relative costs, capital and O & M costs, associated with a sludge transport system are the volume and solids content of the municipal sludge as it leaves the treatment plant. For example, though pipelines operate economically over long distances with dilute sludges, rail tank cars and barges are more cost effective when used with concentrated sludges. The cost of dewatering sludges must be included when determining the optimum sludge-handling strategy. Similarly, the distance to the disposal site is crucial to the determination of the most cost effective method of transport. Cost of land spreading operations currently in progress generally involve transport distances of less than 80 km (50 miles). One notable exception is the Chicago system, in which the sludge is transported almost 320 km (200 miles). For short hauls, tank trucks have proven to be cost effective; but this method is not feasible for long-distance, large-volume sludge hauling.

Climate and local topography also play an important role in determining the transport system. Climate affects the transport system availability. For example, frozen waterways would prohibit barge transport during the

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CHARACTERISTICS OF SLUDGE TRANSPORTATION METHODS

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Sludge State and Mode of Transport	Characteristics	Comments
Rail tank car	Capacity, 100 wet tons (24,000 gal). Need loading and disposal sites near R.R.	Solids will settle while in transit; some form of agitation desirable.
Fixed pipeline (buried)	Suitable for year-round use.	As diameter of pipe increases, pressure loss due to friction decreases (inversely proportional to pipe diameter to the fifth power). Need minimum velocity of 1 fps to keep solids in suspension. High capital costs.
Portable pipeline (surface)	Will freeze if used intermittently, not suitable for winter use unless provision made for draining.	Use at disposal site to provide flexibility in selecting field for disposal.
Tank truck	Capacity, 500 gal up to maximum allowed on road. Can have gravity discharge or forced (pressure or pump) discharge.	Can use for highway transport and field application. Can use large tractor trailer rig for highway transport but must transfer for field application. If flotation tires used for field travel, not recommended for long distance highway travel.
Farm tractor and tank wagon solid	Capacity, 800 to 3,000 gal	Low speed; principal use would be field application, not distance hauling.
Rail hopper car	Need special unloading site and equipment for field disposal.	Possible use when final disposal is of landfill type. Sludge can be flushed from cars to a lagoon for disposal as a slurry.
Trucks, dump or other type	Suitable for wastes or sludges in solid, non-slurried form.	Trucks can be fitted with equipment to spread waste on ground surface. If dump truck used, will need to level sludge piles. Soil incorporation desirable.
Farm wagons or manure spreaders	Suitable for wastes or slurries in solid, non-slurried form.	Principal use would be field application, not distance hauling. Soil incorporation desirable.

Source: Reference 24.

winter months, requiring storage of sludge during this period. Topography also plays an important role in determining the availability of certain transport systems. Barge transport, for example, requires suitable inland waterways leading away from the urban center where the sludge is generated. Similarly, a mountainous terrain or rocky soil might preclude construction of a pipeline for sludge transport.

Required storage volume to level out annual sludge generation/disposal rates is also a major factor in determining transport system cost. This factor is tied in with the flexibility of the transport method (e.g., whether or not more than one transport method must be used in getting the sludge from the sludge treatment plant to the actual disposal site.) If, as for large cities, more than one treatment plant exists, it may be economical to pipe all sludge to a central pipeline facility for pumping to a disposal site out of the urban area. Similarly, if the disposal area consists of discrete parcels of land spread over an entire county, a truck transport system may be necessary from barge unloading or rail unloading facilities. In these cases, additional storage would be required at each unloading facility.

The financial analysis scheme used by the municipality also affects the selection of the sludge transport system. Different cities use different methods of municipal financing, which affect the desirable ratio of capital-to-operating costs. In addition, because the municipality is interested primarily in the cost of sludge disposal it incurs, it may favor capital-intensive methods of sludge transport. The reason is that EPA grants are available for capital construction costs of sludge-treatment-related facilities, whereas operation and maintenance costs are not eligible for grants. The selection may also be affected by the current ownership of land resources, trucks, or other transportation equipment. Finally, if the wastewater treatment system of the municipality already has dewatering equipment, its amortization must be included in evaluating liquid transportation systems as opposed to dewatered sludges.

Data on transportation costs for the current study are developed from a recent report done for EPA by Culp, Wesner, and Culp.²⁵ This report evaluates transportation costs, including loading and unloading facilities, for the four transport methods described. Both liquid and dewatered sludges are examined for transport distances up to 260 km (160 miles). The costs derived are annual equivalent costs based on the actual haulage parameters (i.e., cubic meters of dewatered sludge or liters of liquid sludge transported).

These data stress once again the strong influence of solids concentration on transportation costs. Figures A-3 through A-11 are the derived costs per dry metric ton of sludge solids for sludge transport for nine different sizes of urban centers with populations of 10,000, 25,000, 50,000, 100,000, 200,000, 350,000, 700,000, 2 million, and 4 million. The cost per dry metric ton is calculated on the basis of the annual equivalent cost divided by the annual solids produced by secondary treatment plants that include digestion. This cost assumes a raw sludge generation of 0.104 kg (0.23 lb) per capita-day and a sludge solids production leaving the sewage treatment plant of approximately 0.064 kg (0.14 lb) per capita-day.

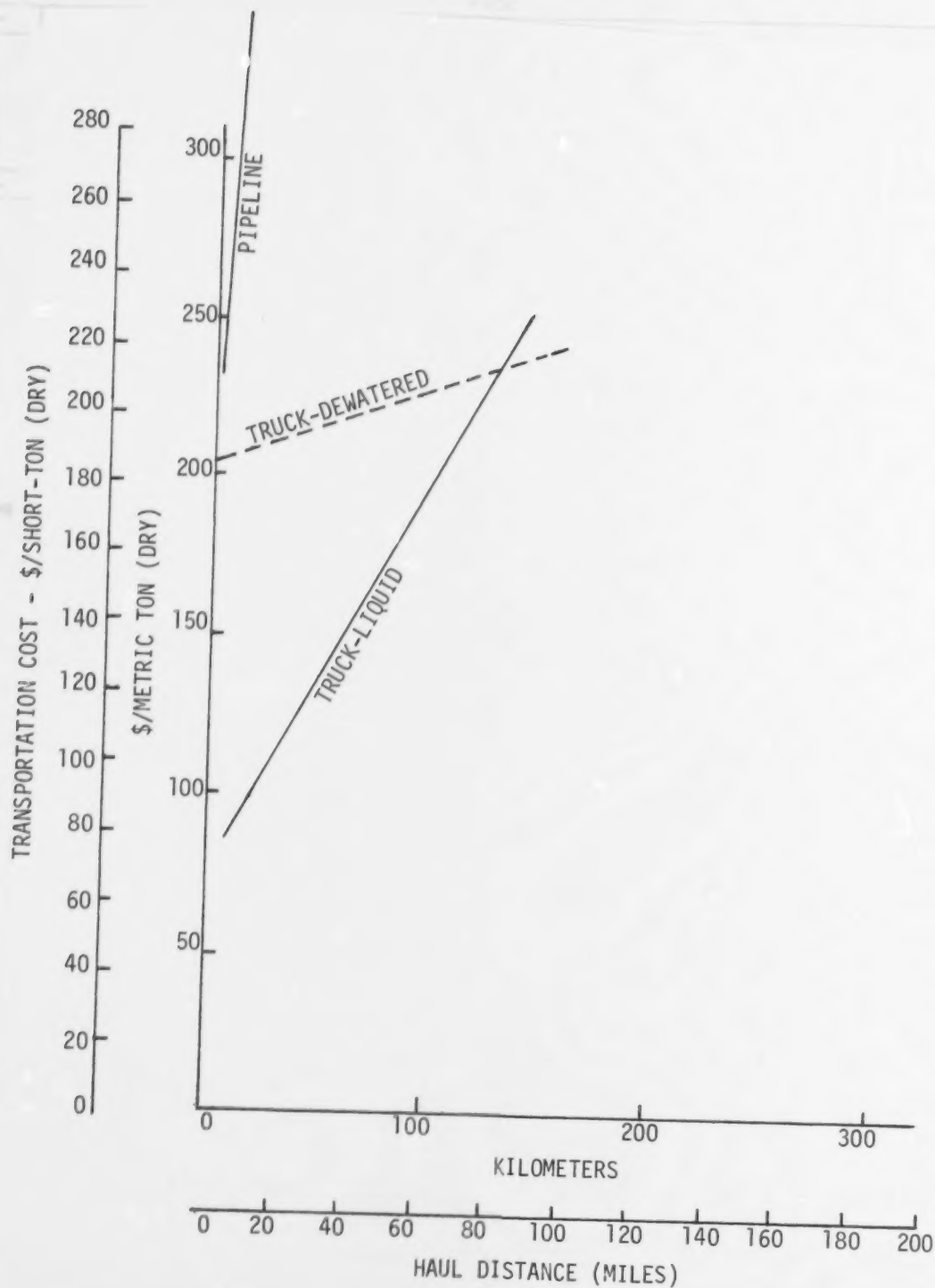


Figure A-3. Cost of sludge transportation (1 mgd).

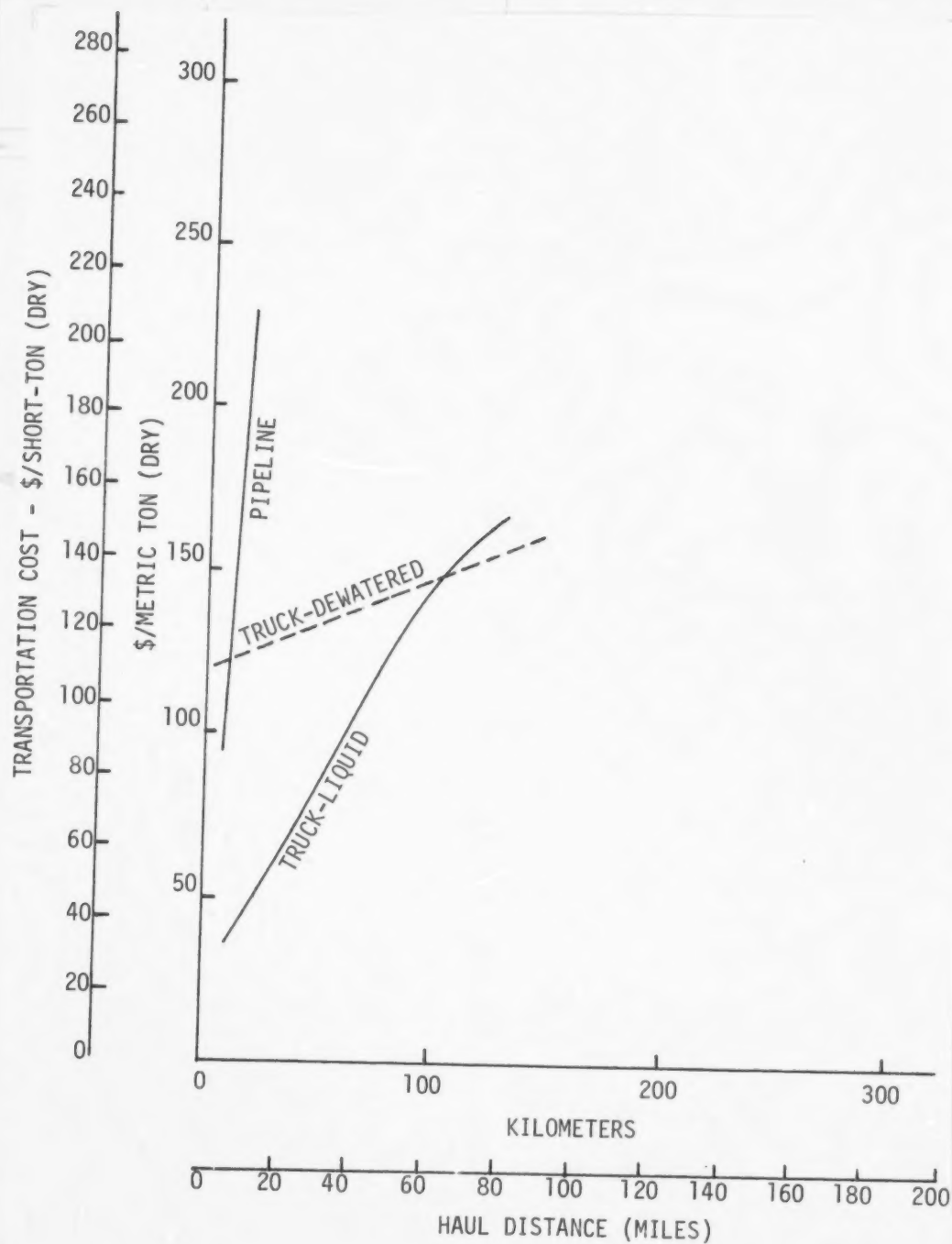


Figure A-4. Cost of sludge transportation (2.5 mgd).

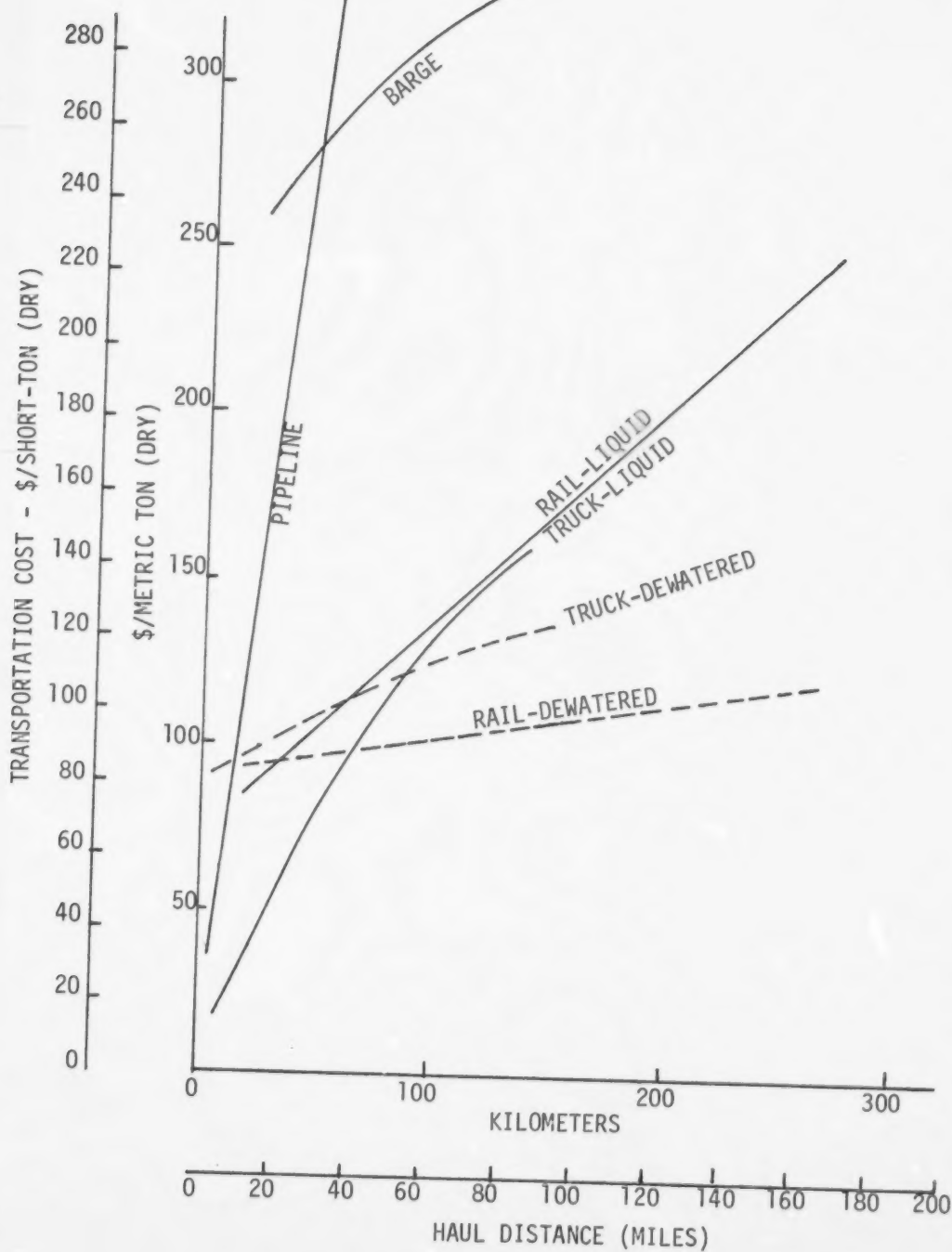


Figure A-5. Cost of sludge transportation (5 mgd).

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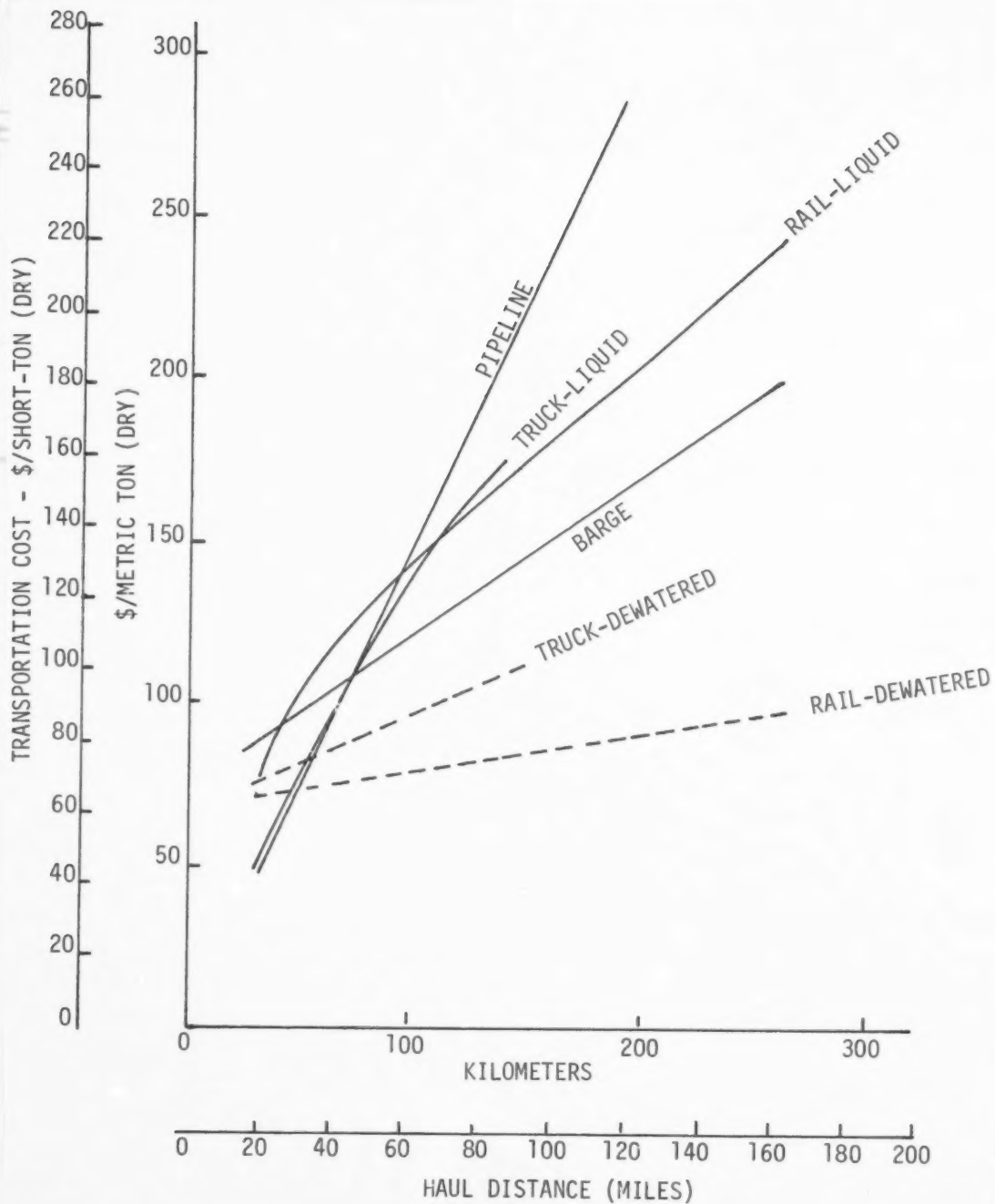


Figure A-7. Cost of sludge transportation (20 mgd).

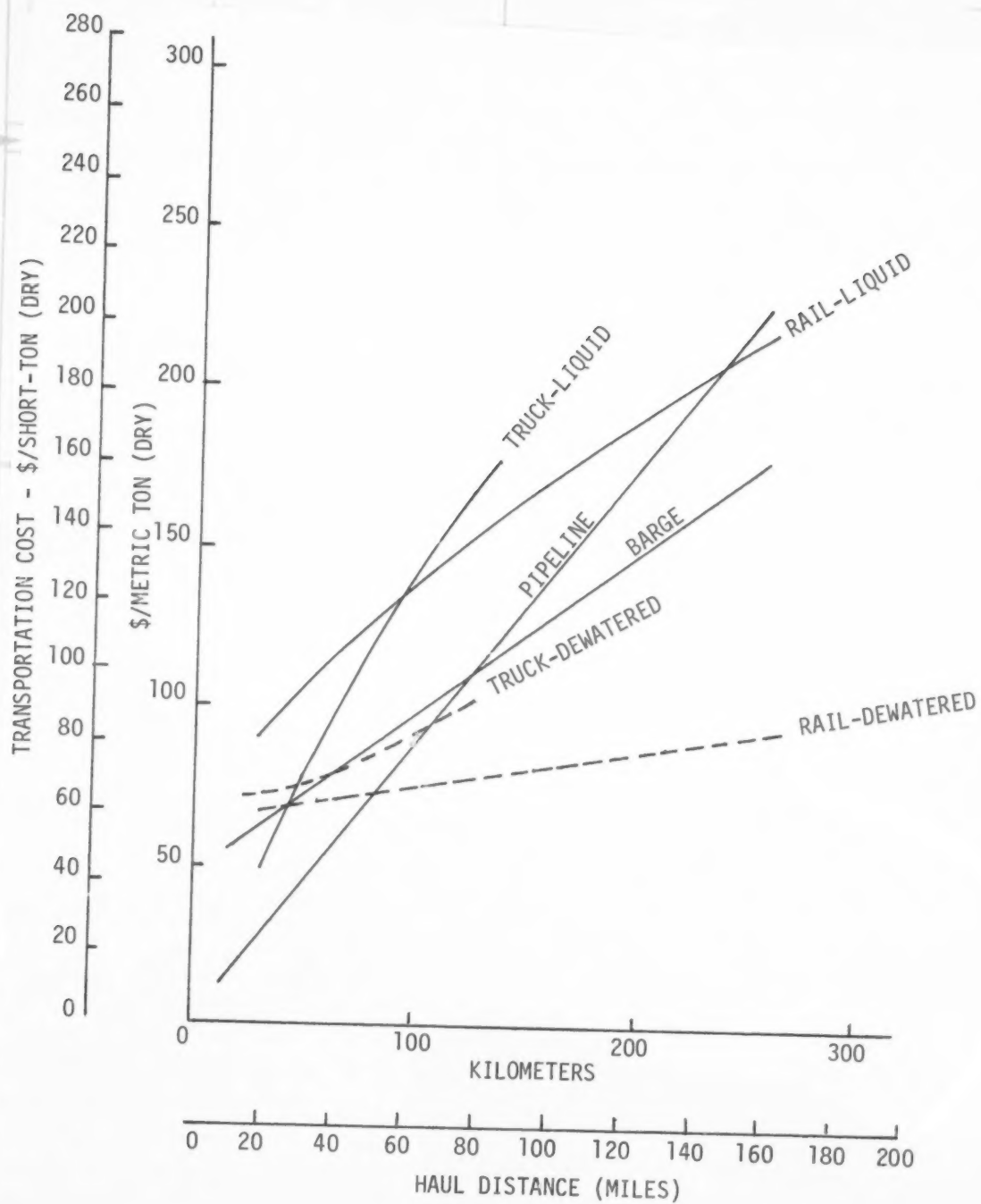


Figure A-8. Cost of sludge transportation (35 mgd).

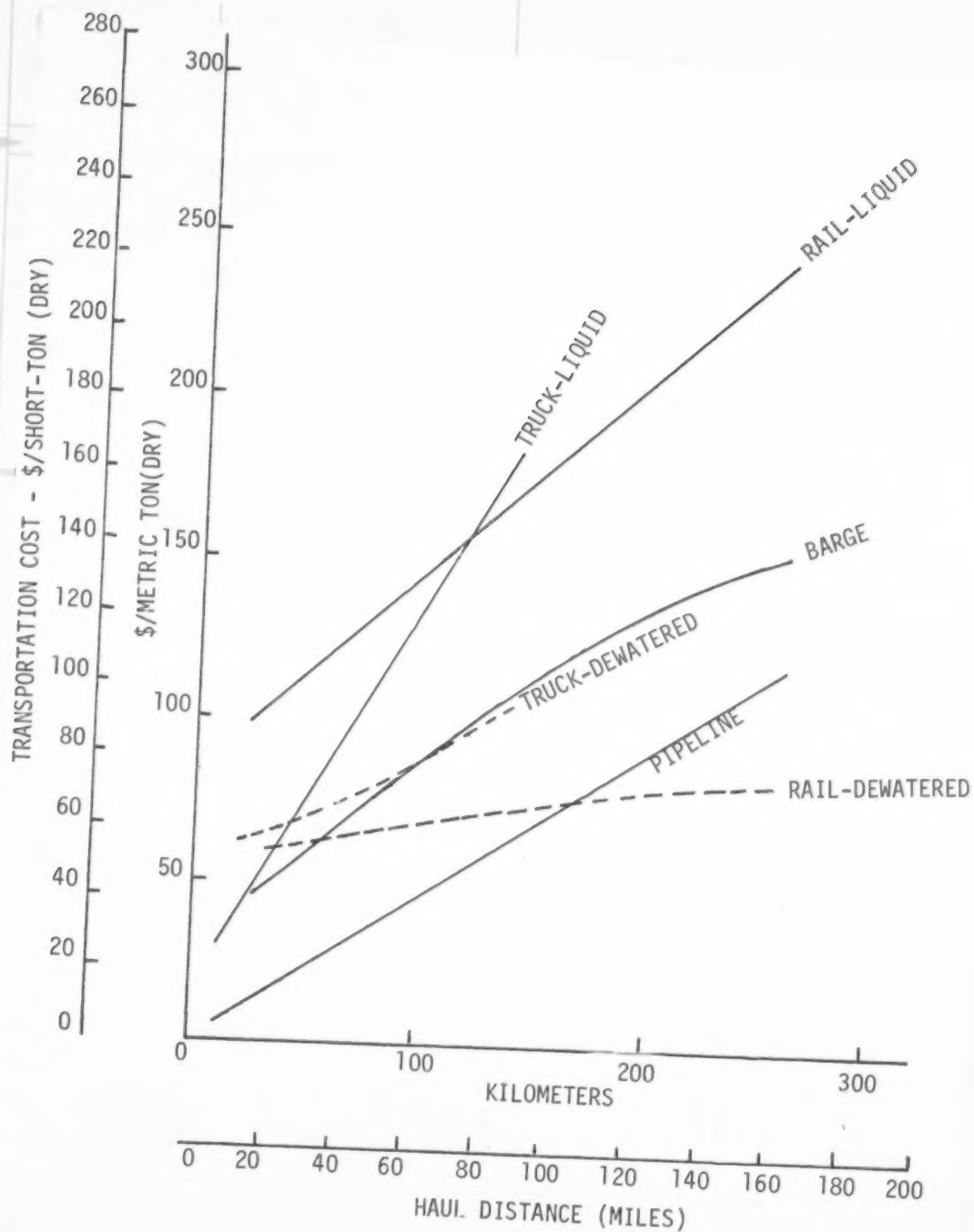


Figure A-9. Cost of sludge transportation (70 mgd).

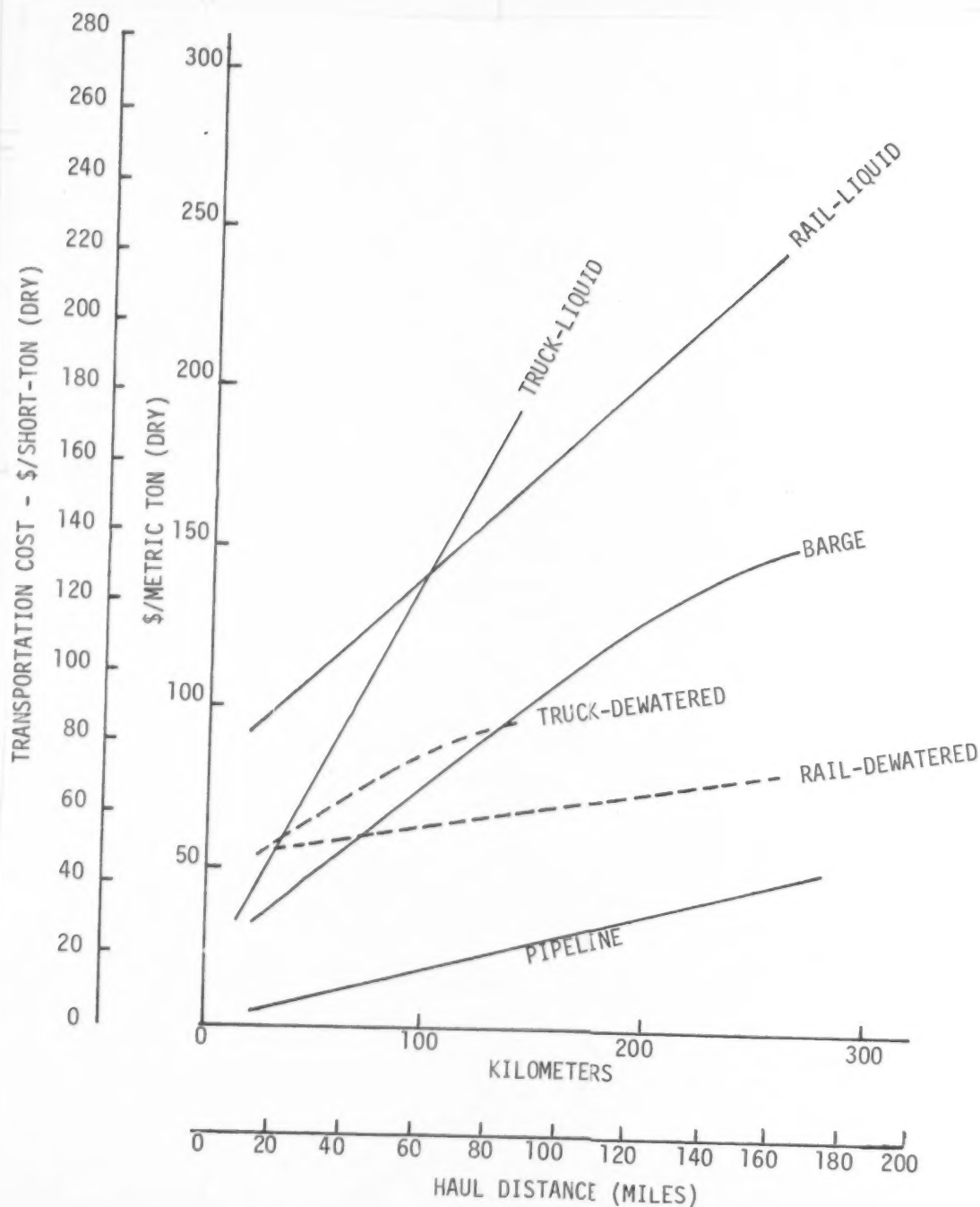


Figure A-10. Cost of sludge transportation (200 mgd).

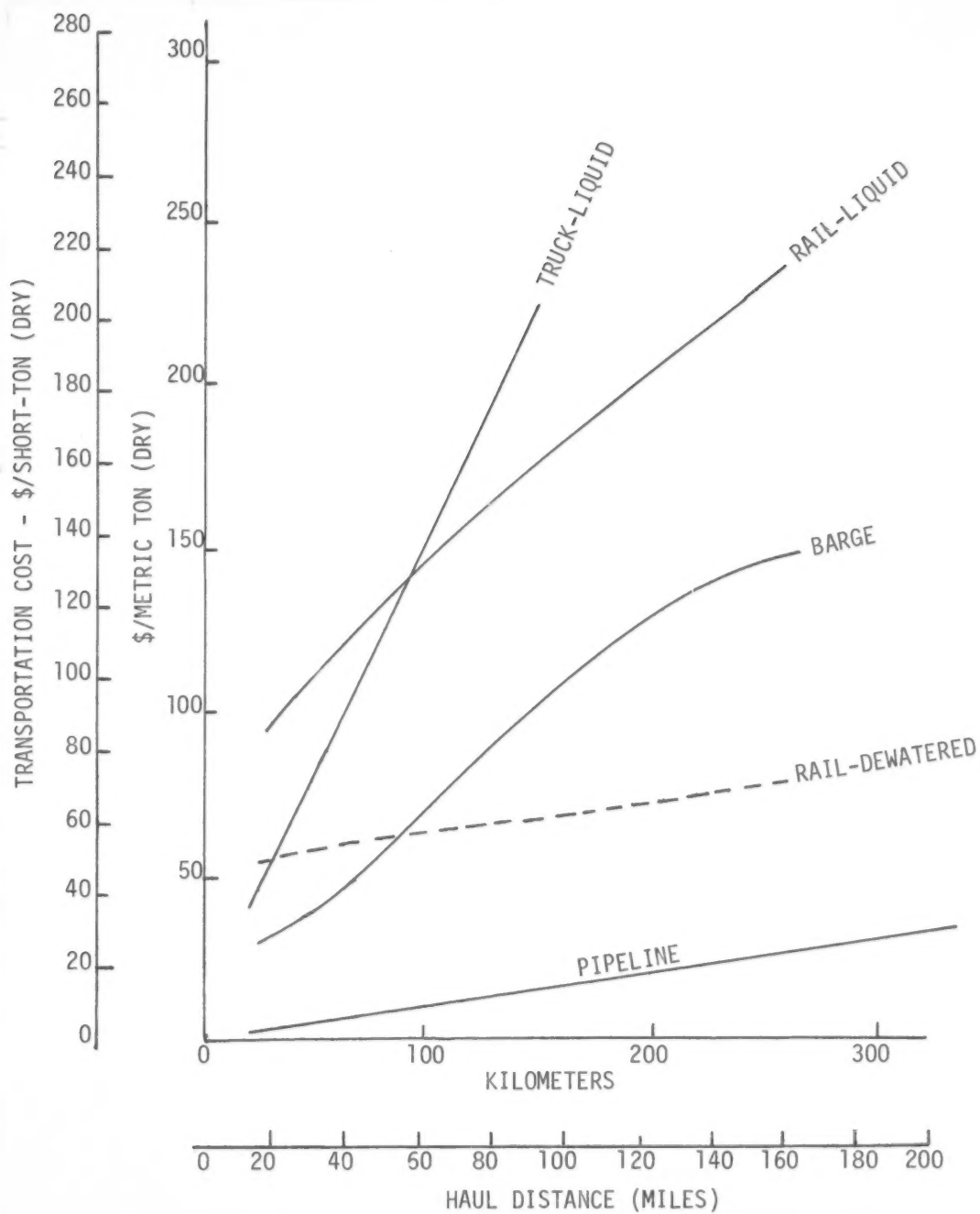


Figure A-11. Cost of sludge transportation (400 mgd).

The figures support what is accepted knowledge in current land-spreading practices: That is, for small towns and short hauls, trucking of liquid sludge is the most economical system. If one remembers that the Culp, Wesner & Culp data have been estimated to be accurate within plus or minus 15%, it is apparent from the figures that for distances beyond about 30 km (20 miles), a variety of other methods become cost effective. Local factors will determine which alternative is most cost effective for each situation. In the larger distances (beyond 100 km, or 60 miles), the hauling of dewatered sludge by rail or the barging of liquid sludge becomes the most economical method. As the size of the towns increases, fixed pipeline becomes the most economical transport system. For towns with populations of 2 million or more, fixed pipeline is the most cost-effective system over the entire range of transport distances.

METHODS OF APPLYING MUNICIPAL SLUDGES TO LAND

Methods of Application

Municipal sludge can be spread on the surface of the land or incorporated into it using either liquid or dewatered sludge. The most common application method presently used is the surface application of digested liquid sludges. Most sludges, with approximately 4% total solids content or less, may be applied through use of spray irrigation or sprinkler systems. This system would include water cannons and other pressure-type sprays. Sludges that are roughly 4% to 10% solids may be applied by ridge and furrow irrigation or overland flow.

Subsurface application (or soil incorporation) of liquid sludges has several advantages over surface application methods. In disposal situations where there is a real or perceived odor problem, subsurface application (SA) prevents escape of sewage sludge odors. Because of these characteristics, SA permits the application of undigested sludge, which has promise as a substitute technology for extremely expensive municipal waste treatment processing. SA might be a more esthetically acceptable alternative for local residents because the sewage sludge is never visible during transportation or application. Methodologies of SA include subsurface injection (using a chisel-type tool to open the soil, followed by pressure application of sludge at varying soil depths) and the plow, furrow, cover method (PFC).²² In this method, sludge is placed in furrows by a tank truck, and a tractor follows behind the sludge wagon covering the sludge in the furrow immediately after it is applied. Another method that has received some attention for subsurface application of liquids is a percolation or tile drain field. This system includes a permanent installation of piping beneath the surface.

The application of dewatered sludges (i.e., sludges with solids contents greater than 20%) allows much higher incorporation rates before runoff becomes a problem. The dewatered sludges can be piled on the land to allow further drainage, and subsequently spread using a box manure spreader. Surface applications of dewatered sludge are limited to relatively light applications of approximately 4.5 metric tons/ha (2 tons/acre) where runoff is a problem.²³ Subsurface applications or soil incorporation of dewatered

sludges permits application rates to be much higher before runoff becomes a problem. Depending on the size of the plow used, up to 1,000 metric tons/ha (450 tons/acre) of dry matter have been incorporated. However, application rates on this order would probably not be acceptable because of nitrate leaching. Table A-9 describes the various systems and gives some of the other advantages and disadvantages of each.

The choice of applying liquid or dewatered sludge is generally a trade-off between the cost of transportation and watering. But several factors affecting application to the energy crops have been considered. Dewatered sludge by its nature requires less volume for storage and is easier to handle using conventional materials handling equipment. On the other hand, the solids are then harder to distribute on row crops. The dewatered sludge may have to be reslurried at the final application site if sufficient water is available. Another consideration is that in dewatering the sludge, much of the nitrogen remains in the water phase at the treatment plant. The fertilizer value of the sludge is thereby reduced, but a higher solids application rate is permitted. Overall, even with the drawback of its storage requirements, liquid sludge may be preferred over dewatered sludge for energy crop applications because of its flexible application on row crops, its small but not negligible irrigation value, and its nitrogen content, which is higher than that of dewatered sludge.

The tradeoffs involved in selecting either surface or subsurface waste applications are much less technical in nature. The primary reason for the selection of subsurface injection currently is the problem of odors and esthetics. Incorporation of the sludge, however, does prevent runoff from land. Spraying and sprinkler irrigation systems allow volatilization of ammonia nitrogen in the liquid sludge. Subsurface application of liquid sludges results in less nitrogen volatilization. A final problem to contend with on subsurface systems is the effect of tillage or permanent piping on the crop being grown.

Sufficient cost data exist in the literature to differentiate between the various surface and subsurface methods of application. As mentioned earlier, the major factors involved in sludge disposal are the transportation and dewatering costs. Studies indicate that the cost of actually applying sludge to the land is on the order of \$20/dry ton, which is approximately 5% to 10% of the total sludge treatment and disposal cost.

Selection of specific application methods for the identified energy crops cannot be based simply on the costs of application. The crops that are being investigated for possible use as energy crops may be divided into two groups--the annual row crops and the perennial woody crops. Annual crops include both the starch and sugar crops (corn, wheat, and sorghum). Perennial crops include hardwoods and softwoods such as southern pine. Each crop presents its own set of special conditions for the land application method. For example, it will be virtually impossible to drive between the rows of annual crops during the growing season. This fact mitigates against use of any subsurface application method other than in-place drainage tile, which would be unworkable because of annual plowing. In addition, another constraint in fertilization of both annual row crops with sewage sludge is that

TABLE A-9
FIELD APPLICATION MODES FOR SLURRIED SLUDGES

Mode	Characteristics	Topographical and Seasonal Suitability	Comments
		SURFACE APPLICATION (Not suitable where odor nuisance is a factor)	
Irrigation spray (sprinkle)	Large orifices required for nozzle. Large power requirement. Low labor requirement. Wide selection of commercial equipment.	Can be used on rough or steep land. Can be used year-round with provision for draining in winter. Not suitable for application to some crops during growing season. Sludges must be flushed from pipes when irrigation stops.	Application rate not recommended to be over $\frac{1}{4}$ in/hr, less if runoff begins to occur. Permanent irrigation set can be used on pasture and woodlands.
Ridge and furrow	Less power requirement than spray irrigation. Land preparation needed.	Between $\frac{1}{8}$ and $1\frac{1}{2}\%$ of slope, depending on percent solids. Can be used in furrows between row crops during growing season. Can be used year-round with provision for draining pipes in winter.	
Overland flow	Used on sloping ground, vegetation controls runoff.	Can be applied from ridge roads.	Suitable for emergency operations. Hard to get uniform applications. Helpful on very poor soil.
Tank truck	Capacity, 500 to 2,000 gal. Larger volume trucks require flotation tires.	Smooth and level or slightly sloping land. Not usable with row crops or soft ground.	Can be used for transport and disposal. With pressure or pump, discharge can be sprayed from roadway along field.
Farm tractor and tank wagon	Capacity 800 to 3,000 gal.	Smooth and level or slightly sloping land. Not usable with row crops or on soft ground.	Can be used with overland flow.

(continued)

TABLE A-9 (continued)

Mode	Characteristics	Topographical and Seasonal Suitability SUB-SURFACE APPLICATION (Suitable to control odors)	Comments
Tank truck with plow furrow cover	Capacity, 500 gal. Single furrow plow mounted on rear of truck.	Smooth and level or slightly sloping land Not usable on wet or frozen soil.	Not suitable for long transport.
Farm tractor and tank wagon with plow furrow cover	Sludge discharge into fur- row ahead of single plow; 170 to 225 wet tons/acre per application (40,000 to 55,000 gal). Sludge spread in narrow swath and immediately covered with plows; 50 to 125 wet tons/acre per application (12,000 to 30,000 gal).	Smooth and level or slightly sloping land. Not usable on wet or frozen soil.	Additional tractor power needed to pull plow. These application rates may cause pollution, de- pending on the amount and the form of nitrogen, i.e., NH ₃ or organic.
Subsurface	Sludge placed in channel opened by tillage tool; 25 to 50 wet tons/acre per application (6,000 to 12,000 gal).	Smooth and level or slightly sloping land. Not usable on wet or frozen soil.	Additional tractor power needed to pull tillage tool. Vehicles should not tra- verse injected area for a week or more.

sludge could not be applied immediately before planting, as there is some evidence that the ammonia concentration in the liquid sludge would inhibit seed germination. Thus two methods remain for land application on the annual row crops--an overland application method using ridge and furrow techniques, or commercial tank trucks with spray (pump) discharge spray system using movable headers, guns, or sprinklers. The primary limitation of the ridge and furrow technique is the evenness of application. Solids are not deposited uniformly, as they trickle down the rows. On the other hand, the spray system applies sludge to the leaf surfaces or stalk surfaces of the plants. Some data suggest that sludge drying on the leaf surfaces will inhibit the growth of these crops and may, in fact, cause increased uptake of heavy metals directly by the leaves.²⁶

The woody perennials have their own set of application problems. With the short-rotation hardwoods at high planting densities, it would be impossible to get in among the trees for subsurface injection, and buried piping would be subject to damage when the hardwoods were dug up and replanted. The woody crops are then faced with the same alternatives as the annual row crops--overland flow or spray irrigation. Preliminary findings from work in Washington State indicate that it is best to apply sludge below the leafy canopy. This procedure could be done using the ridge and furrow technique. In the case of pines, the growth period would be longer and the canopy would be much higher, permitting the use of movable sprays under the canopy. However, subsurface injection might be feasible if the rows in hardwood plantations are sufficiently separated from each other to permit access by tank trucks or tank tractor combinations. Subsurface application may be beneficial, as it provides cultivation of the plantation (weed control) which is necessary for high productivity of the plantation. This method of sludge application was retained in the study and was included in the energy plantation model described in Appendix B.

Climatic Limitations

In most regions of the United States, sludge application to the land is limited by climatic factors (i.e., the temperature is below a certain level, precipitation exceeds a certain amount, or snow cover exceeds a certain depth).

A conservative method of accounting for the temperature effect is to assume that application is suspended when the mean temperature is below 0°C (32°F). The maximum precipitation allowed before application is stopped will depend primarily on the site conditions (maximum infiltration rates and stormwater runoff). In many cases, operation may be assumed during days with 2.5 cm (1 in.) of precipitation.²⁷ In most cases, the limitations on sludge application because of snow and/or ice cover will be similar to those imposed by the temperature conditions.

Earlier work sponsored by EPA has led to the definition of five climatic regions in the continental United States.²⁷ These regions are shown in Figure A-12 and have been used in the analysis of land application of municipal and industrial effluents. The same regions will be used here to characterize the climate-related limitations imposed on land application of sludge.



A - Mediterranean Climate-Dry summer-mild, wet winter

B - Arid Climate-hot, dry

C - Humid Subtropical-mild winter-hot, wet summer (Wash., Ore., area mild, moist summer)

D - Humid Continental-short winter, hot summer

E - Humid Continental-long winter, warm summer

Figure A-12. Climatic regions. (Source: Reference 27.)

Significant differences in climatic conditions do occur within the regions defined in the figure (see Region C for instance), but in each case, average conditions will be defined that are representative of the region. For border-line locations, the climatic conditions of a neighboring region may be used when the analysis of a specific site is performed.

The climatic limitations adopted for the various regions--period of application of the sludge and storage requirements--are shown in Table A-10, which was generated from State-by-State Climatic data.²⁸

Cost of Land Application and Sludge Storage

The costs for land application of sludge reported in the literature display a wide range of values for apparently similar conditions. These variations are due to different methods of accounting, inclusion of land costs, sharing of equipment with other municipal services, etc. A regression analysis of relevant cost figures (i.e., costs apparently including only land spreading from a central point located a few miles from a central sludge collection point) was performed. The data included 27 points published in the literature.^{1,12,28} The resulting cost-population function is shown on Figure A-13.

The correlation coefficient is -0.33, the mean cost value is \$25/dry metric ton (\$22.67/dry short ton), and the standard deviation is \$8.42/dry metric ton (\$7.64/dry short ton). The estimated mean value is close to standard values quoted in the literature (i.e., about \$22/dry metric ton or \$20/dry short ton). Also, reliable cost estimates published for some case studies are very close to the values obtained from Figure A-13.³⁰ Costs for application of dewatered sludge will be lowered in proportion to the solids content.

Figure A-14 shows the cost of storage as a function of population size. For populations larger than about 100,000, the cost of storage remains essentially constant.³¹

LAND COST AND LAND AVAILABILITY

Land Cost

One of the major costs of land disposal of treated sewage sludge is associated with transportation; hence the sludge haul distance becomes critical to economics. Land costs are important to the economics of the production of energy crops. Thus an analysis was made to determine how land costs varied as distance increased from population centers.

Standard metropolitan statistical areas (SMSA's) were used to define five sizes of urban and suburban populations:⁶ greater than 3 million; between 1 and 3 million; between 500,000 and 1 million; between 250,000 and 500,000; and between 100,000 and 250,000. During the analysis, the smallest two categories were incorporated into one when it became apparent that data for both were similar. The analysis also revealed that the land cost/

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TABLE A-10

CLIMATIC REGIONS FOR SLUDGE APPLICATION AND THEIR CHARACTERISTICS

<u>Region</u>	<u>Description</u>	<u>Sludge Application period-days/year</u>	<u>Storage Capacity days</u>
A	Mediterranean Climate-Dry Summer Mild, wet winter	340	0
B	Arid Climate-Hot, dry	300	95
C	Humid Subtropical-mild winter-hot wet summer (Wash., Ore., area-mild, moist winter)	320	45
D	Humid Continental-short winter, hot summer	260	105
E	Humid Continental-long winter, warm summer	245	120

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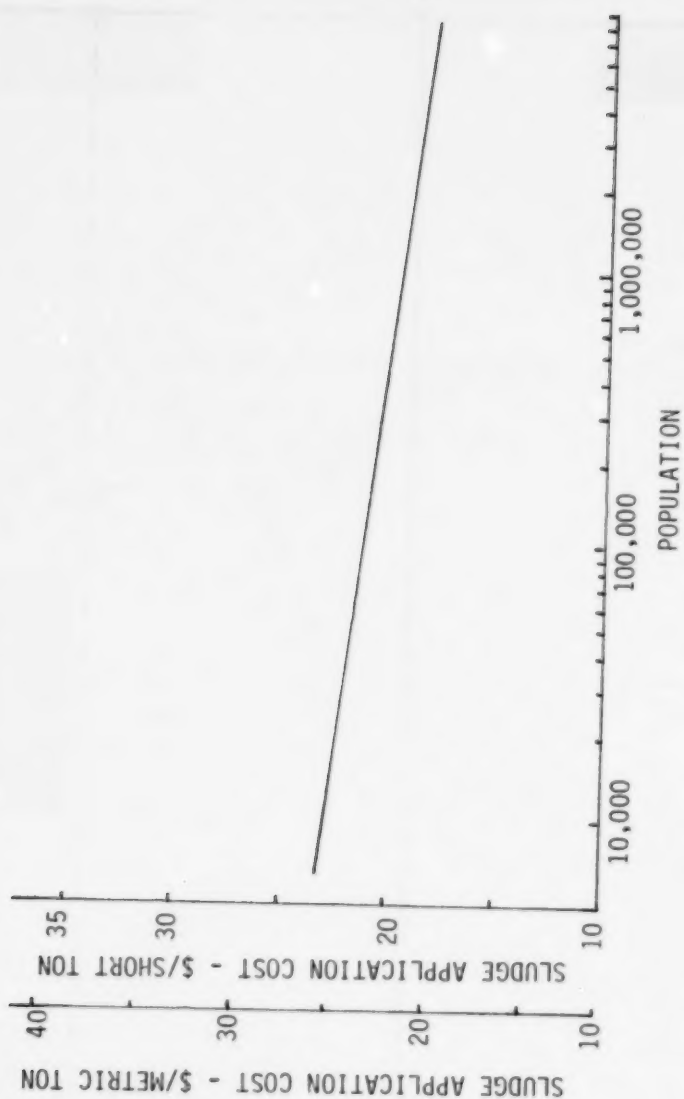


Figure A-13. Cost of Land application of sludge (5% solids).

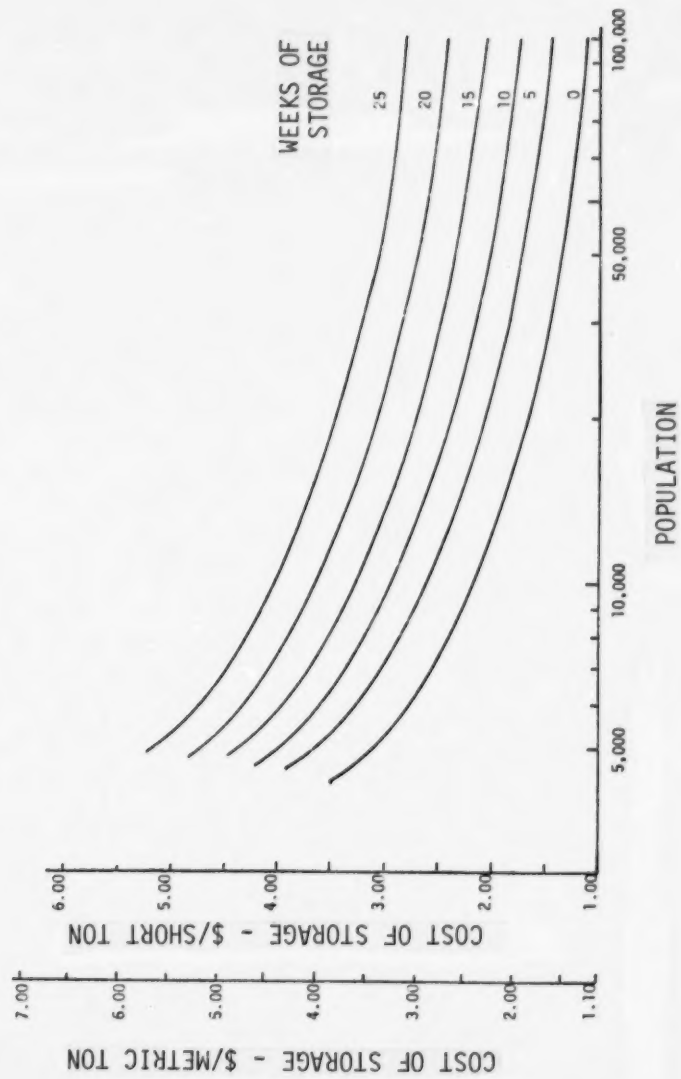


Figure A-14. Cost of sludge storage. Source: Reference 31 - 5% solids sludge.

distance curve for the 100,000 to 250,000 category could be used for cities smaller than 100,000 people.

On a map of the United States, a 320-km (200-mile) radius was drawn for each SMSA analyzed (three SMSA's per size group). The radius emanated from the county in the SMSA with the highest population, or from the city representing the SMSA if the city was independent from surrounding counties. Radii were chosen at random that did not cross into other SMSA's. Epicenters were approximated for all counties that each radius crossed. The distance from the population center to each county epicenter was measured and recorded along with the average value of land and buildings on farms³³ for the county in question.

Data for cost of land and buildings on farms and distances from the population centers were then plotted for the cities in each SMSA size group. A smooth curve was fitted by eye to represent the average value of the three cities in each group. A more precise fitting technique was not justified because of the significant variations in land costs expected as a result of local and regional considerations (real estate, urban development, etc.). Because of these expected variations in land costs, the impact of land cost on the economics of the energy crop approach is considered in the sensitivity analysis. The resulting four curves are shown in Figure A-15.

From this qualitative analysis, two general trends are apparent. First, all the curves tend to flatten out at or just below the national average for the value of land and buildings in farms (about \$300/acre).³³ An average cost of farmland can be used for later analysis of specific cases. Second, the larger the population, the farther one must travel away from the population center to reach the average value. From our analysis, one must travel approximately 40 km (25 miles) from a population center of 100,000 to 500,000, 80 km (50 miles) from a center of 500,000 to 1 million, 130 km (80 miles) from a center of 1 to 3 million, and 320 km (200 miles) from a center larger than 3 million.

The exception to this analysis would be those SMSA's grouped in dense population corridors, such as Boston to Washington, the southeastern coast of Florida, or south central Michigan. Here, where SMSA's are packed together and farmland makes up a small percentage of the total area, land costs are influenced more by real estate prices than by agricultural values.

Note that the land values shown in Figure A-15 are similar to those used earlier in the section on the cost of ultimate sludge disposal. This situation thus ensures consistency in the cost comparison of various methods of sludge disposal (i.e., landfilling and landspreading) with or without crop production.

Land Availability

Land disposal of municipal sludge on energy crops assumes that land will be available for the purpose of growing these crops within a reasonable distance from the municipality of interest. The question addressed here is thus

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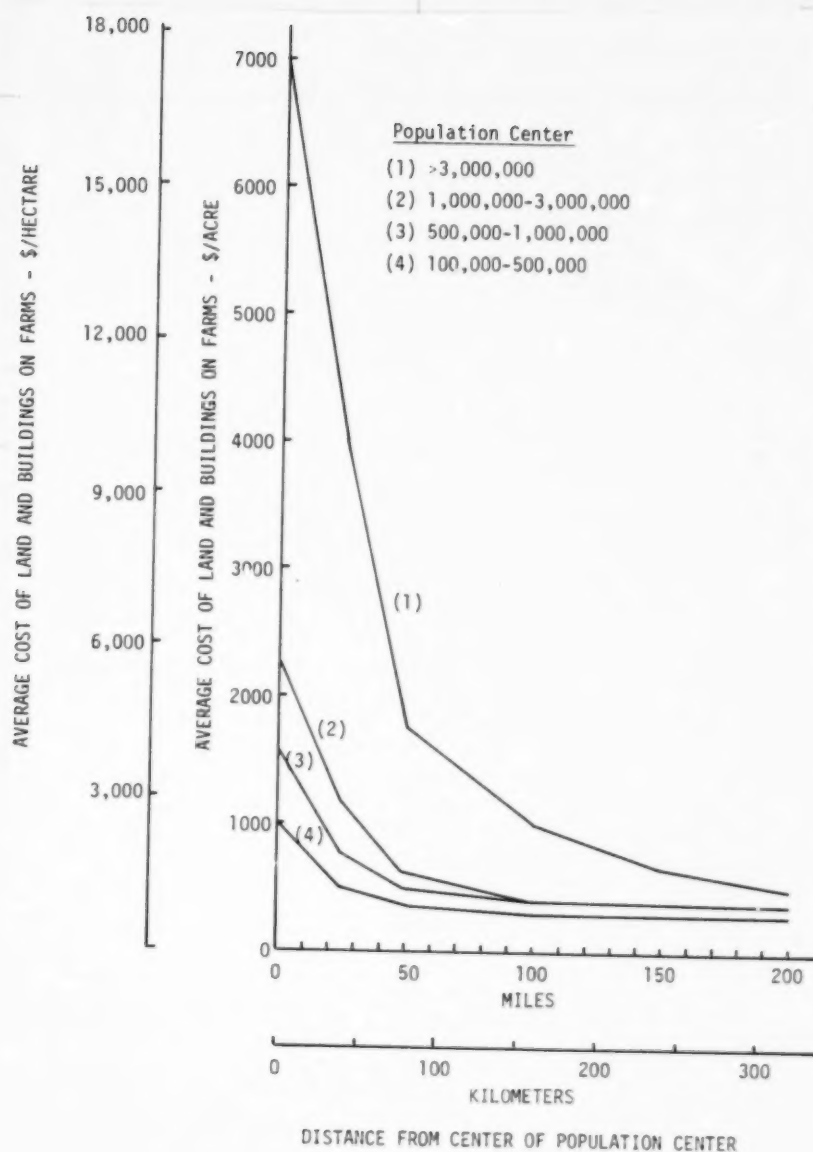


Figure A-15. Cost of land as a function of distance from metropolitan center.

how far is it necessary to haul sludge from the wastewater treatment plant to find enough land to dispose of this sludge?

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A second analysis was thus made to determine the land available as farmland around SMSA's of various sizes. The fraction of land in each county reported as farmland was plotted against the distance of each county's epicenter to the center of the SMSA. The correlation resulting was less precise (as evidenced by the spread of data points) than the first analysis (land cost). Some general trends were, however, observable.

In the first analysis, SMSA's fell into three categories: (1) Larger than 1 million; (2) between 500,000 and 1 million; and (3) under 250,000.

One has to travel about 30 km (20 miles) from the smallest of the three population sizes to find a county where 90% or more of the county area is farmland. One must travel about 40 km (25 miles) from a SMSA with a population of 500,000 to 1 million to find the same fraction of farmland per county. Finally, from SMSA's with populations greater than 1 million, the distance to a county with 90% or more of its land in farmland is about 50 km (30 miles).

In the first analysis (land cost), the question was how far must one travel to get the lowest priced land, hence what is the maximum travel distance. In the second analysis (land availability), a criterion for finding the minimum distance to travel was examined. For the smallest SMSA's (100,000 to 500,000), the two distances were nearly the same--40 and 30 km (25 and 20 miles), respectively. In the other two cases (500,000 to 1 million and more than 1 million), the minimum distance was substantially different from the maximum difference; hence the cost of transportation would be the limiting factor.

For municipalities smaller than the smallest SMSA's considered here (100,000 population), it will be assumed that farmland at the average cost is available at a distance of less than 30 km (20 miles). This assumption is supported by case studies.

Land Distribution

One of the major assumptions made in this study is that energy crops will only be grown on marginal farmland (land classified as farmland but not intensively used or suitable for that purpose). Classes 4 and 6, as defined in the classification of the Soil Conservation Study of the U.S. Department of Agriculture, are potential candidates for energy crop production.³ Land of Class 4 is characterized by slopes on the order of 15%, whereas land of Class 6 has slopes on the order of 20%. Their respective productivities are characterized by indices of 0.75 and 0.35, compared with good farmland of Class 3 with an index of 1.

The analysis of land availability considered total farmland as a function of distance from a population center. An analysis of the distribution of this farmland among the various farmland categories shows that in most cases analyzed, land in Classes 4 and 6 (i.e., land considered for energy crop production and sludge disposal) accounts for 10% to 20% of the total

farmland available. This factor will have to be taken into account when estimating the cost of energy crop production because the distribution of energy cropland in a given geographic area influences the operating costs of the energy farm. Indeed, as described in Appendix B, the energy farm is assumed to be made of separate plots of marginal land between which the farm machinery has to be moved and from which the energy crop has to be transported to its point of use.

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POTENTIAL ENERGY CROP GROWTH AREA

The purpose of this analysis is to define major classes of potential biomass energy crops and to identify geographic regions where these crops either are or could be grown over substantial areas. The major energy crops analyzed are:

- a. biomass crops (moist, cool, temperate areas, deciduous and ever-green trees and shrubs);
- b. biomass or sugar crops (subtropical areas, C₄ grasses [sugar cane] and bamboo);
- c. starch and sugar crops (the Midwest and Great Plains, conventional farm crops); and
- d. latex, oil, and wax crops (warm xeric areas, certain desert shrubs, succulents, etc.).

In each case, the major topographic and edaphic conditions for each crop region are described, and the cationic exchange capacities (CEC) for major soil types are identified.^{34,35,36}

Woody Biomass

Northern Softwoods--

Softwood trees are the primary crop in Regions 1-A, 1-B, and 1-C (see Figure A-16). The raw material harvested is woody biomass and various resins or pitch. Plantations are short-rotation forests that are harvested every 6 to 12 years.

The main places of interest in this region are, in Area 1-A, the New England and New York uplands; in Area 1-B, the Great Lakes lowland and Superior upland; and in Area 1-C, the valleys between the Coast Range and the Olympic and Cascade Mountains.

This northernmost region includes three separate areas of mountains, hills, valleys, and, in the central area, some plains. The annual precipitation is 38 to 64 cm (15 to 25 in.) during the growing season and on level ground, but it varies widely in the mountains. The average annual temperature ranges from 5° to 10° C (40° to 50°F) on level ground, but it is lower at higher elevations and higher along the Pacific Coast. The freeze-free period is about 120 days and fluctuates in the same way as the annual temperature.

Shallow and stony lands are common in hilly areas. Inceptisols and Spodosols are common to slopes and uplands, except in the west where Ultisols predominate. Inceptisols are found throughout the region on low and poorly drained sites. In areas 1-A and 1-B, the northeastern and north central areas, the cationic exchange capacity (CEC) ranges between 8.0 and 15.0 meq/100 g. In the northwest, the CEC varies widely from 5.0 to 50.0 meq/100 g.

In primary deciduous communities, maple and beech are the usual dominants, and in secondary communities, aspen, alder, poplar, and birch are abundant. The coniferous communities that occur throughout the region are of two general types: Those of more or less dry sandy plains and ridges, and those of poorly drained areas, bogs, or meskegs. A third type of coniferous community occupies mesic flats and slopes in the northeastern and western part of the region. Primary mixed communities are found in all three areas in the region.

Central Hardwoods--

Pioneer to mid-climax hardwood trees such as cottonwood, sycamore, sweet gum, and silver maple are typical crops. The raw material harvested is woody biomass, primarily lignin and cellulose. Plantations are usually short-rotation forests, harvested every 2 to 4 years.

The main areas of interest in this region are, in Area 2-A, the Appalachian plateau and the valleys in the Blue Ridge Mountains; in Area 2-B, the interior low plateau; and, in Area 2-C, the Ozark highlands.

This region is considered a borderland between the North and the South. The annual precipitation is 102 to 127 cm (40 to 50 in.), but it ranges from 89 cm (35 in.) along the western edge to 152 cm (60 in.) or more on some of the higher mountains in the East. The freeze-free season is 180 to 300 days, decreasing from south to north and with increasing elevation.

Inceptisols from sandstones and acid shales are the more extensive soils on the mountain slopes and dissected plateaus. Utisols are on limestone and more deeply weathered shales. The Inceptisols have a CEC of about 15 meq/100 g of soil; in the Ultisols, the CEC ranges from 4.0 to 8.0 meq/100 g.

The climax vegetation to the east (mixed-Mesophytic forest) is composed of a large number of dominants, particularly beech, tulip tree, basswood, sugar maple, sweet buckeye, chestnut, red oak, white oak and hemlock. The forests in the central area (western mesophytic forest) are mixed forests, but there is a greater tendency toward the dominance of a few species. In the west, oak-hickory forests are interspersed with prairies.

Southern Hardwoods and Softwoods--

Hardwood and softwood trees are both candidate crops for this region, with hardwoods grown in lowlands and softwoods grown in uplands. The raw material harvested is woody biomass, lignin, cellulose, and resins if the crop is a soft wood. Plantations are usually short-rotation forests. Hardwoods are harvested every 2 to 4 years, and softwoods are harvested every 6 to 12 years.

These crops will be grown in Region 3 (the southern piedmont plateau) and Region 4 (the southern coastal plain). Region 3 is divided into Area 3-A (the Atlantic slope) and Area 3-B (the gulf slope). Region 4 is divided into Area 4-A (the Atlantic coast) and Area 4-B (the gulf coast).

On the piedmont plateau, the annual precipitation is 114 to 140 cm (45 to 55 in.) per year in the east and slightly less in the west. The average annual temperature is 14° to 22°C (57° to 65°F). The average freeze-free period ranges from 200 to 250 days, decreasing from south to north and with elevation.

Ultisols dominate over most of the area. Ultisols are found on uplands underlain by basic crystalline rocks, and poorly drained soils are associated with them on foot slopes and wet upland flats. Shallow Inceptisols are on strongly rolling to steep slopes throughout the area.

Oaks and pines are dominant over much of the area, but pines persist alone in areas less suitable to deciduous species. However, on poorer soils and in drier sites, pines are more or less temporary and are ultimately replaced by deciduous species. This region is transitional between the central deciduous forest and the southern evergreen forest.

The southernmost region is composed of the coastal plain and the southern Mississippi Valley uplands. The average annual precipitation is from 102 to 152 cm (40 to 60 in.). The average annual temperature ranges from 16° to 20°C (60° to 68°F), increasing from north to south. The freeze-free period is 200 to 280 days, again increasing with decreasing latitude.

Ultisols are dominant throughout. Associated with them on wet lowlands are gley poorly drained soils. The Ultisols have a CEC ranging from 4.0 to 8.0 meq/100 g, whereas the poorly drained soil CEC ranges from 8.0 to 12.0 meq/100 g.

The most prominent vegetation feature of much of this region is the preponderance of evergreen trees. The long-leaf pine forests of the sandy uplands dominate the landscape of much of the Atlantic and gulf coast plain. Scarcely a forest community exists, upland or lowland, without some admixture of coniferous or broad-leaved evergreen trees or shrubs. The deciduous woody plants form the subdominant layer of the forest.

Sugar from Sugar Crops

Three major sugar crops are grown in the United States: Sugar cane, sugar beets, and sweet sorghum. All three crops are harvested for the syrup contained in each, which is primarily sucrose. Sugar beets and sorghum are annual crops, but sugar cane is generally treated as a biennial, planted and harvested every 2 years.

The total acreage planted in the continental United States in both sugar cane and sugar beets is small, so sweet sorghum was analyzed as the major sugar crop. Sweet sorghum is extensively grown from north Texas to south

central Nebraska (see Region 6-C on the map). The average annual precipitation is 41 to 76 cm (20 to 30 in.) over much of the region, but it ranges from 38 to 89 cm (15 to 35 in.), increasing from northwest to southeast. More rain falls during summer than in the rest of the year. Average annual temperatures are 10° to 18°C (50° to 65°F), increasing from north to south. The freeze-free season is 170 to 180 days in most of the region, but it ranges from 150 to 240 days, increasing in length from north to south.

The important soils in the north are in the Mollisols and Ultisols. Aridisols are extensive in the south. Lithosols on steep slopes, Entisols in deep sands, and alluvial soils on flood plains are common throughout the region. The CEC ranges from 23.0 to 40.0 meq/100 on the major soil types within this area.

Starch from Annual Grain Crops

Conventional small grain and corn crops are grown for their grain, from which the starch is produced. Only the major crop-growing areas in the mid-west and high plains dedicate large areas to this kind of crop.

The Midwest and Ontario-Mohawk Plain--

One major grain-producing area is the corn belt from western Ohio to eastern Kansas, Nebraska, and South Dakota (see Region 6-E on the map).

Fertile soils and favorable climate make this one of the outstanding grain-producing regions of the world. The annual precipitation is 64 to 89 cm (25 to 35 in.) over much of the region, but it ranges from 41 cm (20 in.) in the extreme northwest to 114 cm (45 in.) along the eastern and south-eastern fringe. Somewhat more than half falls during the growing season. Average annual temperatures are 8° to 13°C (45° to 55°F) in much of the region, but they range from 5°C (40°F) in the extreme northwest to 17°C (63°F) in the extreme southwest. The freeze-free period is 140 to 180 days in most of the region, but it may be as short as 130 days along the northern fringe and as long as 235 days in the extreme southwest.

Alfisols in the east and Mollisols in the west are the dominant soils. Mollisols and Entisols on wet lowlands, and alluvial soils in bands along the major streams are also important. The CEC of Alfisols in the east is approximately 13.0, and for Mollisols in the west, it is 23.0 to 28.0 meq/100 g.

Northern Great Plains--

The fertile soils and the dominantly smooth topography of this region are favorable for agriculture, but the low rainfall and short growing season severely restrict the crops that can be grown. The annual precipitation ranges from 25 to 60 cm (10 to 24 in.), and a large part of it occurs during the growing season. Average annual temperatures are 5° to 8°C (40° to 45°F) over most of the region. The freeze-free season ranges from 100 to 145 days, increasing in length from north to south.

Mollisols are dominant in most of the region. Other important soils are Inceptisols on steep slopes; Aridisols in terraces and depressions; and narrow bands of Inceptisols along the major streams. The CEC of the Mollisols is 24 to 34 meq/100 g.

Latex, Wax, and Fatty Oil Crops from Desert Shrubs

Region 5 includes semiarid and arid places where one might grow certain desert shrubs or succulents for their latex or wax. Area 5-A to the southwest is made up of plateaus, plains, and basins. Area 5-B to the northeast is composed of arid valleys in the Rocky Mountains. Unfortunately, too little information is available about this class of crop to investigate it further.

Western Great Plains--

In this section of the Great Plains, unfavorable soils, strong slopes, or low moisture supplies make successful dryfarming very uncertain. The annual precipitation ranges from 28 to 60 cm (11 to 24 in.), but it fluctuates widely from year to year. Average annual temperatures are 8°C (45°F) in much of the region, but they range from 5°C (40°F) in the north to 16°C (60°F) in the south. The freeze-free season ranges from 100 days in the north to 200 days in the south.

Mollisols are dominant over much of the region, but Aridisols are important in the west. Entisols on the more sloping parts of the dissected areas, Aridisols in sands, and Entisols on flood plains are also extensive. Less extensive but important locally are Vertisols in heavy clays and Aridisols in depressions and on terraces. The CEC is 24 to 34 meq/100 g for Mollisols and approximately 18 meq/100 g for brown soils.

Southwestern Plains--

This region consists of the warmer part of the southern Great Plains. The moderate precipitation is accompanied by high temperatures so that precipitation effectiveness is low. The average annual precipitation is 51 to 76 cm (20 to 30 in.) over most of the region, but it ranges from 38 to 89 cm (15 to 35 in.). Usually much of it falls in spring and autumn. Average annual temperatures are 16° to 22°C (60° to 70°F), and the freeze-free season ranges from 220 to 320 days, increasing in length from north to south.

The soils in the deeper coarse- and medium-texture materials are mostly in the Aridisol order. Vertisols from limestones and marls, and Inceptisols in all kinds of parent material on hilly to steep slopes are also fairly extensive. The Aridisols have CEC's ranging from 16 to 24 meq/100 g.

Both hardwood and softwood crops are produced in this region. Softwoods grown in the uplands are used as woody biomass, lignin, cellulose and resins. Plantations are usually short rotation forests.

SELECTED ENERGY CROPS AND CONVERSION METHODS

Selected Energy Crops

Analyses in the preceding subsection defined four classes of potential energy crops (sugar crops, grain crops, hardwoods and softwoods, and desert shrubs), and they indicated the general areas within the United States where these crops are most likely to grow or be grown.

Effective and economic production of energy crops requires intensive field operations and land management techniques comparable with those used in agriculture. Little is known concerning the growth potential of desert shrubs under managed conditions (fertilization, cultivation, etc.). The techniques of production of sugar and grain crops are well known. These crops will be retained in the analysis as potential candidates for the areas indicated in Figure A-16 (Areas 6-C, 6-D, and 6-E). A detailed analysis performed by ITC/Solar³⁷ has shown that fast-growing hardwoods can be grown essentially anywhere in the United States, provided sufficient nutrients and water are available. The concept of generating woody biomass for fuel rather than for pulp or lumber value (the Energy PlantationTM concept) is described in some detail in Appendix B, as it plays a major role in the present study. The Energy PlantationTM concept originally designed for hardwoods can be modified to generate biomass from softwood plantations. In most situations, however, softwood energy plantations are economically less attractive than hardwood energy plantations. The impact of the higher cost of softwood production compared with hardwoods on the energy-crop-from-sludge approach is discussed in the sensitivity analysis (Section 6).

Table A-11 identifies the energy crops retained for further analysis in this study.

Conversion Processes

Sugar Crops--

Battelle's extensive study^{39,40,41} of fuels from sugarcane, sweet sorghum, and sugarbeets indicates that ethanol is the only fuel from sugar crops with any potential for cost effectiveness. Ethanol by fermentation is expected to cost the same as synthetic ethanol by 1980.³⁹ The estimated production costs in a plant designed expressly for deriving ethanol from sugarcane at 786 m³/day is \$0.31 to \$0.34/liter (\$1.17 to \$1.29/gal).³⁹ This price includes a credit for the byproduct stillage of \$0.05/liter (\$0.19/gal).³⁹ (Stillage is sold as a cattle feed.) The current bulk selling price of ethanol is \$0.30/liter (\$1.14/gal).³⁹ Even when ethanol does become cost competitive, its impact as an automotive fuel is limited. To produce 27 x 10⁹ liters (7 x 10⁹ gal) of alcohol--7% of the 1976 gasoline demand-- would require 4 x 10⁶ ha (9.9 x 10⁶ acres), or 15 times the area currently dedicated to this crop in the U.S. mainland.⁴⁸ One of Battelle's conclusions is that to manufacture ethanol on a large scale at reasonable cost from sugar crops is beyond the present state of the art.⁴⁸

Because of the low energy value of ethanol versus gasoline, ethanol has virtually no chance of acting as a motor fuel by itself. In a mixture with

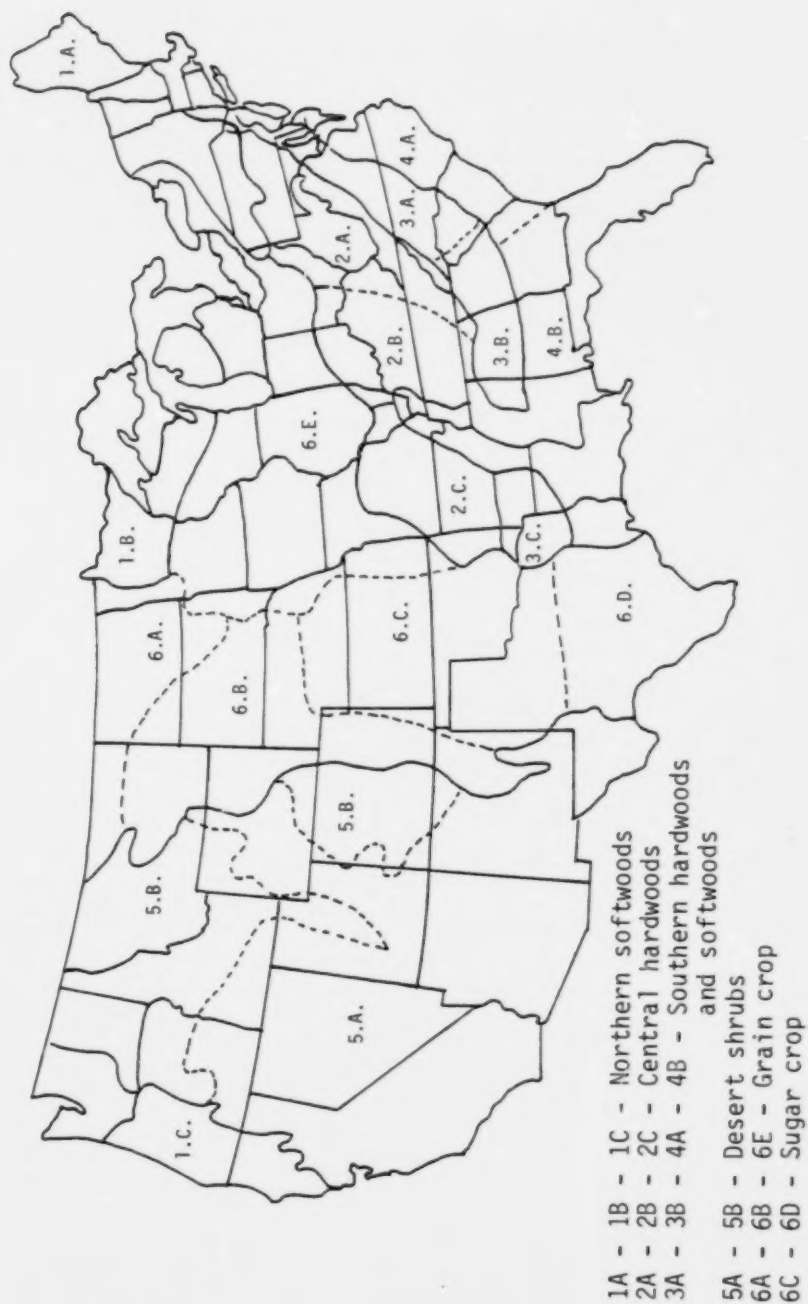


Figure A-16. Growth areas of potential energy crops.

TABLE A-11

ENERGY CROPS SELECTED FOR FURTHER ANALYSIS

<u>Energy Crop</u>	<u>Production Method</u>	<u>Growing Areas</u>	<u>Comments</u>
Hardwoods	Fast growing species, short rotations, multiple harvests, i.e. Energy Plantation ^R (1)concept.	Most regions of the U.S.	Requires irrigation in some regions of the U.S.
Softwood	Fast growing varieties, short rotations, i.e. modified Energy Plantation ^R (1).	Some regions of the U.S.	Requires irrigation in some regions of
Sugar Crops	Agricultural techniques	Region 6C on Figure A-16	
Grain Crops	Agricultural techniques	Regions 6E on Figure A-16	

(1) See Appendix B for a description of the Energy Plantation^R concept.

gasoline, however, it does have utility and is currently being used in some petroleum-poor countries. Brazil currently has several operating alcohol-from-sugarcane plants ranging in size from 60 to 300 m³/day (16 x 10³ to 79 x 10³ gal/day). Ethanol from a 150-m³/day (40 x 10³-gal/day) plant must be fed with 895 metric tons/day (987 tons/day) of sugarcane. At 54 tons/ha-year (24 tons/acre-year) (Brazilian yields), about 3,000 ha (7,400 acres) would be required, assuming the plant operates 180 days a year.⁴⁸ This land is enough to satisfy the sludge disposal needs of more than 3.5 million people if sludge is spread at a rate of 25 metric tons/ha-year (11 tons/acre-year).

Extracting sugar juices from sugar crops is a well established and optimized process. Once extracted, the sugar juice processing is virtually the same regardless of the original source of juice.³⁸ From an energy standpoint, the conversion routes that have the best prospects are those in which the coproducts are used in a highly integrated fashion.⁴⁸ Traditionally the bagasse, or cane fiber, is burned at the sugar mill for steam and power. Pulp left over from sugarbeet processing has such a high food value--ten times the fuel value--that it is not burned, and therefore other fuels must be used.³⁸ Sugarbeet tops have a high moisture content and poor economics regarding collection and transportation.³⁸ The bulk of the tops (0.90 kg/kg of root) is responsible for the poor economics.³⁹ Battelle asserts that sugarcane is the best near- and short-term source of fermentable sugars, with sweet sorghum having the best long-term potential.³⁹

Few byproducts of value result from the distillation of alcohol. The most important is stillage, which carries proteins, some residual sugars, and, in some instances, vitamin products. This product is currently sold as cattle feed. Some aldehyde and amyl alcohol also form. These two chemicals are retrieved in the processing, but no information on quantities was available in the literature.³⁸

Other fuels from sugar crop residues such as methane, methanol, and thermochemical substitute natural gas (SNG) are indeed possible. But a synthesis gas process tailored specifically for biomass is needed before development can occur. Anaerobic digestion of sugar crop products to SNG is ruled out on economic grounds. The state of the art is primitive, and major increases in knowledge are necessary.³⁹ Much more research has been done on the digestion of municipal wastes. If an analogy is drawn between municipal wastes and sugar crop byproducts, it would be reasonable to assign a cost of \$5.50/GJ (\$5.80/MM Btu) to the generation of methane by digestion, which is more than double the current cost of natural gas.³⁹

Starch Crop Corn--

As in the sugar crop analysis, Battelle's investigation into fuels from corn indicates that ethanol is the only fuel with a reasonable possibility of being cost effective using state-of-the-art technology. A large plant producing 788 m³/day (208 x 10³ gal/day) 330 days/year could produce ethanol at \$0.31/liter (\$1.17/gal). This figure includes a \$0.10/liter (\$0.38/gal) credit for the stillage.⁴⁰ The potential contribution to the energy needs of the country is not significant, as it would require 60% of the 1976 corn crop to meet 1% of U.S. energy requirements.⁴⁸ Corn stover or silage has

future potential for SNG, but this can only be considered in the long range. Silage is presently too important as cattle feed.³⁹

Land requirements to feed an ethanol plant of the size discussed above are staggering when compared with land requirements for sludge disposal. This plant would consume the entire corn production of 97,000 ha (240,000 acres) at 247 bushels/ha (100 bushels/acre).³⁹ This amount of land would satisfy the sludge disposal needs of 120 million people at about 25 metric tons of sludge/ha·year. Battelle considers the scale of this plant to be a minimum for economical production of ethanol from corn.³⁹

Fuels from Wood--

Modern equipment for burning wood is virtually unlimited in diversity, and applications range from residential space heating to large steam and electric generating systems. Wood has been used as a fuel by direct combustion for thousands of years, but many other fuels can be obtained from wood. Figure A-17 illustrates the numerous chemicals and other byproducts that are possible. The chemicals of interest are obtained primarily through distillation of the wood. Pyrolysis, or destructive distillation, is the principal chemical conversion taking place in this process. Currently only waste woods, primarily hardwoods, are treated in this manner.³⁸ Table A-12 lists the yields from the pyrolysis of one cord. The higher the pyrolysis temperature, the greater the formation of gaseous products. Pyrolysis at 810°C (1,500°F) yields the products shown in Table A-13. Methanol can be produced from wood gas, yielding 325 tons of methanol from 1,000 tons of oven-dry wood. The cost, however, appears prohibitive. Production costs are estimated at \$111 to \$128 (±20%)/metric ton, not including capital costs, depreciation, profit, or general overheads.⁴² More complicated and expensive processing make it possible to produce synthetic crude oil from the wood gas. But research is in its infancy, and costs are expected to be approximately \$21.35/barrel, not including capital investment, transportation to refinery, taxes, and profit.⁴²

The byproduct char from low-temperature pyrolysis, because of its low sulfur and nitrogen content, is an attractive fuel to mix with high-sulfur coal and oil. Tests have shown that mixing char or wood with high-sulfur coal or oil can result in stack exhausts requiring no emission control devices other than a baghouse or an electrostatic precipitator.⁴³

Softwoods or coniferous woods, because of their high resin contents, are steam distilled rather than being destructively distilled. The primary products are resin and turpentine. The wood, which leaves the process intact and very dry, is burned for process heat.⁴³ No other fuels from softwoods were discussed in the literature.

Although several fuels can be produced from wood, Table A-14 shows that to obtain the maximum energy from wood, direct combustion is the preferred route. Two primary wood-burning systems are used to generate steam or electricity: Semi-suspension and suspension firing. Both involve feeding wood from above and air from below. In the semi-suspension system, a large part of the fuel drops to the bottom and burns on the grate. The suspension furnace, which requires a smaller particle size, holds the particle above the grate long enough to effect almost complete combustion of the particle

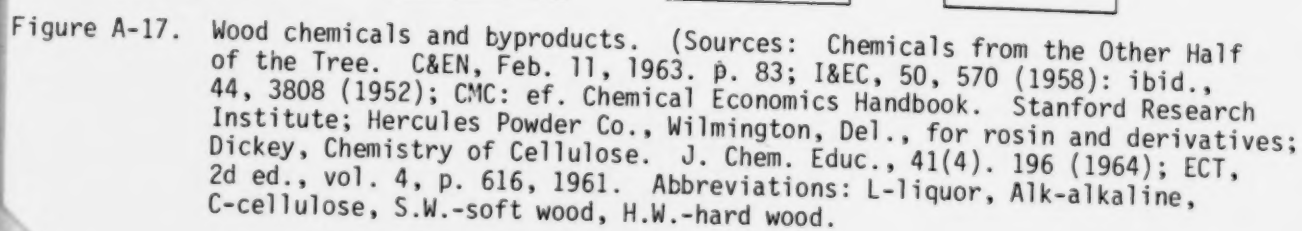


TABLE A-12
YIELD UPON DISTILLATION OF ONE CORD OF WOOD

Condensable Gas	7-11,500 ft ³
Charcoal	900-1080 lb
Raw pyroligneous acid	200-276 gal
Acetate of Lime	180-220 lb
^L Acetic acid equivalent	108-125 lb
Crude Methanol	99.5-11 gal
^L Refined	7.25-8.5 gal
Wood tar and oils	22-25 gal

Source: Reference 38.

TABLE A-13
PYROLYSIS OF WOOD AT 810°C

<u>Products</u>	<u>% wt of Feedstock (00)</u>
Wood Gas	89.5
Tar	8.0
Ash	2.5

<u>Wood Gas Composition</u>	<u>% Volume</u>
CO ₂	2.12
CO	27.7
CH ₄	16.9
C ₂ H ₄ + higher	8.7
H ₂	25.5

Net Heat of Combustion 441 Btu/ft³

Source: Reference 42.

TABLE A-14
COMPARATIVE ENERGY RECOVERY FROM WOOD

COMPOUND	YIELD/T OD ¹	PRODUCT	TOTAL POTENTIAL HEAT VALUE MM BTU/T OD ⁵
		HEAT VALUE BTU	
WOOD DIRECT BURNING	2,000 LB ³	8,500/LB	17.0
CHARCOAL	670 LB	12,500/LB	8.38
OIL	370 LB ²	14,380/LB	5.32
METHANOL	647 LB	9,788/LB	6.33

¹ T OD = TONS, OVEN DRY.

² 1.25 BBL OR 52.5 GAL BASED ON 7 LB/GAL AND 42 GAL/BBL.

³ Multiply by 0.4536 to express in kg.

⁴ Multiply by 2.3259×10^3 to express in joules/kg.

⁵ Multiply by 1.163 to express in GH/metric ton.

before it falls to the grate.⁴⁴ Aside from standard boilers, these suspension or fluidized-bed furnaces can be used in conjunction with a gas turbine.⁴⁵

Table A-15 illustrates the costs per kWh for various electrical generating systems. A 20-megawatt facility, as illustrated in Table A-15, would require about 240 tons/day of wood @ 20% moisture, assuming a 0.6 load factor. To supply this much wood on a continuous basis would require approximately 4,000 ha (9,900 acres) of tree farm.³⁷ The major drawback to the large-scale acceptance of wood as an energy supply is the cost associated with the collection and transportation of the wood to the processing site.⁴⁴ Wood in chip form currently sells for about \$10 per green ton, and transportation costs are approximately \$.05/ton-mile.

Very little research has been done on the anaerobic digestion of wood to produce methane. An investigation by ITC/Solar showed that with state-of-the-art technology, methane could be produced at approximately \$5.00/10⁶ scf. If certain assumptions were made about possible system improvements, that cost could conceivably be reduced to \$3.73/10⁶ scf.⁴⁷

Selected Conversion Processes

Table A-16 lists the various conversion processes of energy crops discussed in the previous section. The list is certainly not exhaustive, but it includes most processes considered presently to generate energy from biomass.

From the preceding discussions of fuels from biomass, it is readily apparent that to be economical, the chemical process plants must be far too large to be supplied only with crops from sludge-fertilized fields, except in the case of a very large city. Existing alcohol plants could, however, use crops from sludge-fertilized fields to meet a portion of their raw material requirements. Conceivably, any heavy metals or other contaminants could be diluted enough so that they no longer presented a problem. For example, a community with a population of 100,000 could support about 80 ha (200 acres) of sludge-fertilized cropland. If this land were dedicated to corn, its yield would amount to 0.08% of the annual raw material requirements of the alcohol-from-corn facility discussed earlier. Direct combustion of wood presents a special opportunity of its own. The same community (or groups of communities with a combined population of 100,000) could support a tree farm generating about 800 cords of wood per year. Though this amount could not support an electrical generating plant, it could supply a significant amount of wood for home or industrial heating.

Table A-17 lists the conversion processes and forms of energy crops retained in the analysis together with their present value. The probable value of a fuel or form of energy in 1985 is obtained by applying an annual inflation factor and a socio-technico-economic factor to present prices.⁴⁹ To compare the present value of energy/fuels with that of energy crop energy/fuels, apply the noninflation rate of increase to present prices, since inflation is the same for both fossil fuels and energy crop operation. This noninflation rate of increase is assumed to be 3% for coal and electricity, 5.5% for oil, and 13% for natural gas. Present values of fossil fuels as

TABLE A-15 - COMPARATIVE POWER GENERATION COSTS¹

Plant Type	Installed Cost (\$/kW)	Estimated 1980 Fuel Cost (\$/10 ⁶ Btu)	Heat Rate (Btu/kWh)	Fuel Cost (mills/kWh)	Owning Cost ² (mills/kWh)	Manpower ² Cost (mills/kWh)	Total Cost (mills/kWh)
Nuclear	\$1,100	\$0.75	10,500	7.9	27.5	---	35.4
Coal steam	\$ 950	\$1.10	9,200	10.1	23.8	2.5	36.4
Wood steam	\$1,000	\$0.50	12,600	6.3	25.00	3.0	34.3
Oil steam	\$ 850	\$2.15	9,100	19.8	21.3	2.0	42.9
Wood gas turbine	\$ 500	\$0.50	17,200	8.7	12.5	3.0	24.2
Oil gas turbine	\$ 220	\$2.60	10,000	26.3	5.5	2.0	33.8

¹ A portion of the data was obtained from GAS TURBINE WORLD, November 1975, "FT 50 Design Shortcut to 1980 Technology," by Victor de Biasi.

² Based on amortization at 20 percent per year and operation for 8,000 hr/yr.

³ Based on a 20,000-kW plant except for nuclear. No estimates made for nuclear.

TABLE A-16

CONVERSION PROCESSES OF ENERGY CROPS

<u>Crop</u>	<u>Process</u>	<u>Product</u>	<u>Comments</u>
Sugar Crop	Fermentation	Ethanol	Large size plants required for economics
	Anaerobic digestion	Synthetic natural Gas (SNG)	Long term technology
Grain Crop	Fermentation	Ethanol	Large size plants required for economics
	Anaerobic digestion (silage or stover)	SNG	Uneconomical
Wood Crops	Combustion	Power	Electricity or steam
	Distillation	Gas	Uneconomical
		Charcoal	
		Methanol	
		Chemicals	
	Distillation	Gas -- Methanol -- Oil	Uneconomical
		Wood Chips Firewood	Chip sold as raw material or fuel

TABLE A-17
SELECTED CONVERSION PROCESSES AND FORMS OF ENERGY CROPS

Energy Crop	Product and Usage	\$/metric ton ⁽¹⁾	\$/short ton ⁽¹⁾	\$/10 ⁶ Btu ⁽⁵⁾
Wood	Wood chips as raw material	11	10	-
	Wood chip as fuel	11	10	1.00 ⁽²⁾
	Wood chip to electricity	--	--	8 ⁽³⁾ - 40 ⁽³⁾
Sugar Crop	Ethanol	--	--	19.95 ⁽⁴⁾
Grain Crop	Ethanol	--	--	19.95 ⁽⁴⁾

(1) Cost excluding transportation.

(2) This cost corresponds to a cost of \$35/cord (air dry) for firewood delivered in rural areas. In suburban areas the cost delivered reaches \$70/cord or about \$2/10⁶ Btu.

(3) Range of value corresponding to cost of electricity of 2 to 10¢/kWh adjusted by a 3% increase factor to 1985 but excluding normal inflation.

(4) Market value of \$0.30/liter (\$/gal) adjusted by a 3% increase factor to 1985 but excluding normal inflation and energy content of 72,190 Btu/gal. (5% H₂O).

(5) Multiply values by 0.95 to obtain \$/GJ.

defined above are given in Table A-18 for the various climatic regions used in this study. The values quoted in the table are those with which the fuel value of energy crops should be compared.

NUTRIENTS AND WATER BALANCE - RATE OF SLUDGE APPLICATION

High-yielding energy crops can be grown on a sustained basis only if sufficient water and nutrients are available to the plantation during each growing season. The nutrient and water balance for each candidate energy crop will in turn determine the sludge application rate to the land and thus the land area required to dispose of the sludge for a given population. As discussed in Appendix B, the total area required for sludge disposal may be composed of a number of individual parcels.

The results of the analysis performed in Appendix C are summarized in Table A-19, which shows that hardwoods will require irrigation in Regions A and B. An alternative is to use desert shrubs or chaparral. No data were found concerning the response of these species to management and fertilization. A yield of 11 oven-dry metric tons/hectare-year (5 oven-dry short tons/acre-year) is assumed, which is about twice the yield of unmanaged natural stands.⁵² The nutrient requirements were assumed to be identical to those of hardwoods. Because sorghum has been determined to offer the best long-term prospect as an energy crop (see Appendix A), the study concentrated on it. Although sorghum is now grown mainly in Region C, it has been shown and is expected to be produced in other regions.* Grain corn grown in Region D (which includes the corn belt) has been chosen to evaluate the concept of grain crops, even though they can be grown in other regions

PRODUCTION COSTS OF ENERGY CROPS AND ENERGY

Woody Crops

The computer model described in Appendix B was used to evaluate the cost of production of woody crops delivered in the form of wood chips at the center of the plantation. The computer printout was adjusted to include sludge storage costs, the cost of supplementary nutrients (mostly potassium), and the cost of subsurface sludge application. The resulting estimate does not include the cost for sludge transportation to the plantation and land costs. For plantations smaller than about 4,200 ha (10,000 acres), or for populations of 1 to 2 million, we assume (see Appendix B) that all plantation operations are subcontracted to local operators rather than run by separate independent energy crop operations. Thus for the small plantations, we assumed that the municipality would supply administrative support only for planning and scheduling of the field operations. Results of the analysis are illustrated in Figure A-18. For large populations (i.e., plantations that are 4,200 ha, or 10,000 acres, or more), production costs are very similar for all regions: About \$11/metric ton (\$10/short ton). This effect results

*Some of the data for sorghums were derived from data for silage corn, which has similar growth characteristics.

TABLE A-18

PRESENT VALUES OF FUELS USED IN 1985

Region	Coal	$\$/10^6$ Btu ⁽¹⁾	
		Oil	Natural Gas
A	1.00	3.23	5.88
B	0.58	3.84	2.52
C	1.08	3.09	2.70
D	1.07	2.94	1.92
E	1.32	3.19	4.38

(1) Multiply values by 0.95 to obtain \$/GJ.

TABLE A-19
WATER REQUIREMENTS AND RATES OF APPLICATION
OF SLUDGE

Region	Hardwoods			Sugar Crops		
	Irrigation (1)	Rate of Application (2) DHT/h-y	DST/a-y (3)	Irrigation (1)	Rate of Application (2) DHT/h-y	DST/a-y (3)
A	+	10-12.6	4.5-5.6 (4)	+	22.2	9.9 (6)
B	+	12.1-15.0	5.4-6.7	+	26.6	11.9
C	0	10.8-13.5	4.8-6.0	0	23.9	10.6
D	0	12.3-15.2	5.5-6.8	0	27.0	12.1
E	0	12.6-15.7	5.6-7.0	0	27.8	12.4

(1) +: irrigation required 0: irrigation not necessary.

(2) Dry metric ton per hectare-year.

(3) Dry short ton per acre-year.

(4) Rates for 10 and 8 oven-dry ton/a-y.

(5) Assuming 5 oven-dry ton/a-y managed plantations of desert shrubs.

(6) Rate for 5,000 lb of sugar/acre-year (25 tons of biomass/acre-year), (40).

(7) Rate for 150 bushels of corn/acre-year (16% dry weight basis moisture) or 4.2 dry ton/acre-year.

TABLE A-19 (CONTINUED)
WATER REQUIREMENTS AND RATES OF APPLICATION
OF SLUDGE

<u>Region</u>	<u>Grain Crops</u>			<u>Shrubs</u>		
	<u>Irrigation</u>	<u>Rate of Application</u> <u>DHT/h-y</u> (2)	<u>DST/a-y</u> (3)	<u>Irrigation</u>	<u>Rate of Application</u> <u>DHT/h-y</u> (2)	<u>DST/a-y</u> (3)
A	+	16.8	7.5	0	6.3	2.8 ⁽⁶⁾
B	+	20.1	9.0	0	7.6	3.4 ⁽⁵⁾
C	0	18.1	8.0	-	-	-
D	0	20.5	9.2	-	-	-
E	0	21.1	9.4	-	-	-

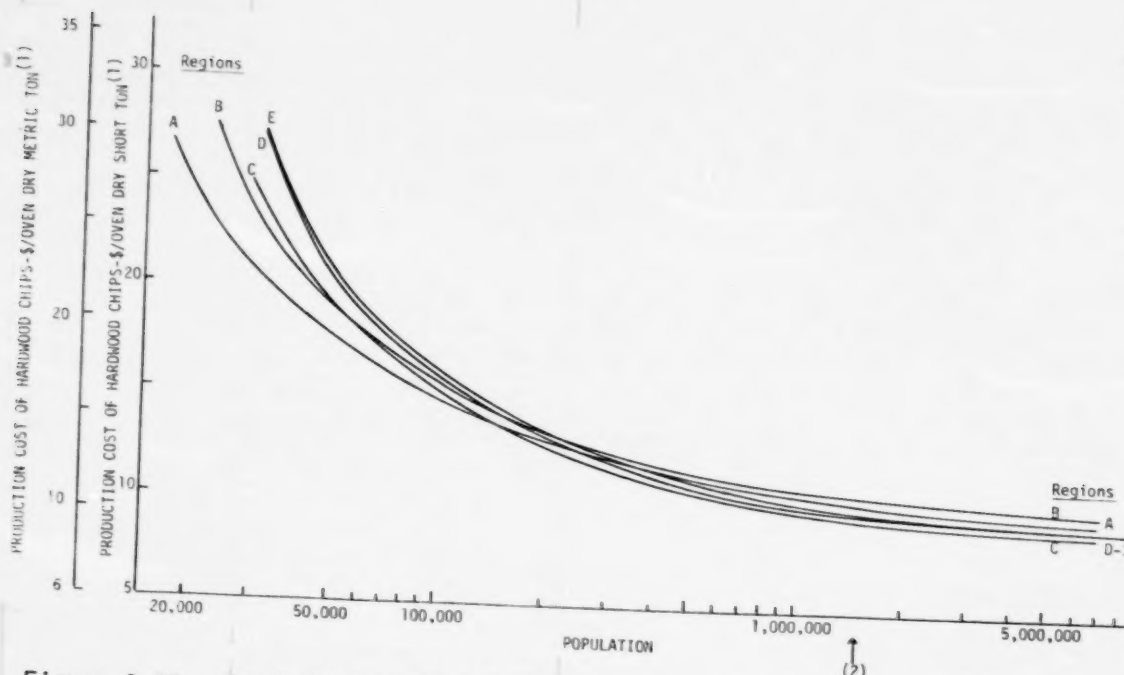


Figure A-18. Production cost of hardwood chips as a function of sewerage population for five climatic regions. (1) (2)

Notes:

1. Costs do not include sludge transportation and land costs.
2. Arrow indicates approximate population size below which it is more economical to subcontract the field operations to local agricultural operators rather than to set up an independent energy farm.
3. Yields of about 8 oven-dry metric tons/ha·year (8 oven-dry short tons/acre·year) are assumed for Regions C, D, and E. Yields of this order have been assumed for managed desert shrubs adapted to Regions A and B.

from the cost benefit of large-scale operations and the integrated use of the plantation equipment and personnel. For smaller plantations, the differences in production cost become significant and are due to various regional factors such as storage requirements, duration of the period during which field operations can be performed, cost of fuels and supplementary fertilizer, etc. It should be stressed that the costs quoted in Figure A-18 are consistent with previous estimates and current wood chip costs.^{37,54}

The major uncertainty in production costs results from uncertain costs for land application of sludge: We estimated that the production costs of Figure A-18 would be about 20% higher for small plantations and about 10% higher for large plantations.

Electricity from Woody Energy Crops

The power plant computer model described in Appendix B is used to estimate the cost of electricity production from woody energy crops. The major cost input to the power plant model is the cost of production of the woody energy crops. The cost of biomass used equals the production cost estimated in the preceding subsection (Woody Crops) plus the cost of sludge transportation and the cost of land. The method for estimating the combined minimum land and sludge transportation cost is described in Appendix D. The cost of electricity production depends strongly on the size of the power plant and thus on the size of the plantation supplying the biomass or on the size of the city generating sludge. Because of the high investment cost of small power plants (\$/kW installed), only power plants of about 15 to 20 MW or larger are attractive from an economical standpoint. Approximately 4,000 ha (10,000 acres) or more would be required to supply the fuel for such plants. The cost of producing electricity will depend on local conditions (climate, for example) and must be estimated on a case-by-case basis. For small plantations (about 4,000 ha or 10,000 acres, which in most cases corresponds to a sludge-producing population of about 2 million), the production cost is about \$0.07 per kWh.

Sugar Crops

Reported production costs for sugar crops are about \$26/dry metric ton (\$24/dry ton) for sorghum, \$36/dry metric ton (\$33/dry ton) for silage corn, \$44/dry metric ton (\$40/dry ton) for sugar cane, and \$57/dry metric ton (\$52/dry ton) for sugar beets.^{39,41} Cost variations of $\pm 15\%$ are recorded. The above production costs do not include those for land, fertilizer (which, except for the potassium, is supplied by the sludge), or sludge transportation to the plantation.

Grain Crops

The cost of producing corn grain is about \$48/dry metric ton (\$44/dry ton), excluding land, fertilizer, and sludge transportation costs.⁴⁰ Cost variations of $\pm 10\%$ are reported.

APPENDIX B

WOODY ENERGY CROPS - THE ENERGY PLANTATIONTM CONCEPT

INTRODUCTION

The use of biomass (agricultural or forest crops and/or their residue) as fuels or raw material for chemical processes is not new. Indeed, wood products still constitute a major source of fuel in many countries.⁶

Biomass in its various forms is an attractive source of energy because it collects and stores low-intensity solar energy through photosynthesis. The plant matter can be used directly as solid fuel or transformed into a variety of synthetic fuels, and the available energy can be released at high temperature. Thus biomass fuels have high thermodynamic availability. Biomass is also a renewable resource that can be produced and used with little or no adverse environmental impact. For instance, biomass fuels contain little sulfur, and their combustion does not modify the carbon dioxide balance of the earth as does the burning of fossil fuels. Moreover, none of the problems associated with the use of nuclear fuels is encountered with plant-matter fuels.

THE ENERGY PLANTATIONTM CONCEPT

The Energy PlantationTM concept first developed by InterTechnology/Solar Corporation in 1971 is a systematic approach to the production of economic fuel from plant matter on a large scale. One of the major problems involved is choosing the planting density and harvesting schedule of the most appropriate plant for optimum collection and conversion of solar energy.

An obvious way of generating plant matter for fuel is to harvest wild vegetation growing on land otherwise unsuitable or unused for agriculture. No planting or managing costs would be incurred, and the land could be accorded some usefulness. Depending on wild vegetation has a number of disadvantages, however. First, annual yields of plant matter per acre from natural stands are only a fourth to a half of what can be achieved in managed plantings.⁶² Higher yields are possible with management because planting density or spacing between plants can be specified to maximize the product of the yield per plant multiplied by the number of surviving plants for a particular harvest schedule. Moreover, natural growth is usually a mixture of many species that produce plant material at different rates; in a managed planting, high-yielding species can be chosen that are well adapted to the site and produce biomass at a known and predictable rate. In a wild stand, even where particular species predominate, the ages of individual plants

usually vary considerably. The resulting variation in plant size makes mechanized harvesting operations difficult and, hence, costly. The age, size, form, and structure of managed plants can be kept reasonably uniform, thereby facilitating mechanical harvesting and processing. Finally, the indiscriminate exploitation of forest land without proper land management can lead to serious environmental and associated economic problems, as witnessed, for instance, in some areas of the Middle East.

Qualitative analysis indicates that perennial species are preferable to annuals for several reasons. First, growing annuals creates troublesome manpower and equipment utilization problems. Annuals must be started at about the same time every year, when soil moisture and other conditions are optimum for the species being planted. They must also be harvested during a relatively short period after they mature. Thus much of the field machinery and manpower needed are in use only a few days per year, unless arrangements are made to move the machinery and operators from site to site as the planting and harvesting activities move up and down the country.

Yields from annuals can be high, but they are achieved only on land that can be given intense soil preparation before planting (that is, the land in demand now or in the near future for food production). Growing fuel on such land is not likely to win ready public support. Another disadvantage of annuals is the high cost of producing plant matter from them. Biomass from annual crops that are harvested all at one time would have to be stored between harvests and preserved against biological degradation during storage. The preservation and proper storage provisions would undoubtedly be costly.

By contrast to annuals, perennials can be harvested more or less continuously throughout the year in response to the demand for fuel. The harvesting machinery, transportation equipment, and personnel involved can therefore be programmed for more continuous use. Consequently, a permanent equipment and work force can be established for these cyclical operations in the plantation. The preservation of perennial crops is accomplished by nature until the plants are harvested, as long as they are alive in the field.

Qualitative analyses as well as quantitative data on plant growth rates indicate that deciduous woody species are preferable to conifers for Energy PlantationTM culture. Data on plant-matter production rates indicate that conifers generally grow more slowly in shorter rotations than deciduous species. An additional advantage of deciduous species is that many will sprout vigorously from their stumps after their structure above ground has been harvested. Since planting costs are a substantial part of the costs of producing any crop, those deciduous species that sprout readily from their stumps and hence provide several crops per planting have an advantage over other species that do not. Few conifers sprout after they have been cut down.

Some deciduous species that grow rapidly when they are young and sprout vigorously from the stumps after being harvested can also be reproduced vegetatively from clones (a live stick cut from a plant that will grow rapidly after storage under moist and cool conditions); this trait is not shared by conifers. Vegetative reproduction has numerous advantages over reproduction from seeds. First, it is far easier and cheaper to collect clones than

seeds from trees. Second, clones produce plants genetically identical to those from which they are cut, whereas seeds may not. Clones can be collected from plants already growing in the plantation; a nursery is thus unnecessary, since the clones are already adapted to local plantation conditions. They can be planted directly in the land where the plants are to be grown, making transplanting unnecessary. This list of advantages indicates that the costs of collecting and planting clones will be far lower than the costs of collecting seeds, germinating them, and transplanting the seedlings to the plantation site.

A number of well known deciduous species have these desirable characteristics. Some varieties are members of hybrid families developed for propagation in a wide variety of soil types and climates. The hybrid poplars are an example of such a family. Other desirable species are natural ones with several varieties that are suitable for a variety of soil and climate conditions if selected carefully. The cottonwoods are an example.

Yield data for some of these species grown at high planting densities and on short rotation cycles have been generated in recent years. These data constitute the basis for the estimates of the fuel production potential of the Energy Plantation TM.

The major characteristics of the energy plantation as it is conceived here thus include:

1. The use of marginal land areas;
2. Reliance on natural water supplies (rainfall mostly);
3. Land management (i.e., insuring that an adequate nutrient balance is maintained so that the productivity of the land can be sustained);
4. Use of fast-growing deciduous species capable of supplying several harvests (coppice harvests) from the same set of roots, thus avoiding replanting after each harvest; and
5. Optimized land use for minimum biomass fuel cost by the appropriate choice of planting densities, harvesting schedules, and cultural practices.

Medium- to large-scale, wood-fired boilers are currently used in many locations in the United States. Electricity and/or steam generation from such units may thus be considered as existing technology. Wood chips supplied by the plantation are predried to about 20% moisture and screened before being fed to the boiler. The screened dirt and ash from the boiler are returned to the plantation to recover as much nutrient value as possible.

COMPUTER MODELING OF THE ENERGY PLANTATION™-POWER PLANT COMPLEX

Recently, InterTechnology/Solar Corporation developed a comprehensive techno-economical model for an Energy Plantation™ power plant complex. The major features of the model are shown in Figure B-1 and are briefly discussed below.

Site Selection

The purpose of this step in the overall plantation power plant design process is to select sites or areas for which the Energy Plantation™ concept might be beneficial economically and socially.

In the present study, sites are assumed to be available for energy crop production in all five of the climatic regions defined in Appendix A.

As indicated earlier, land considered for biomass fuel production only takes into account unused or under-used land (i.e., land that can be converted to biomass production without interfering with other uses such as recreation, agriculture, etc.).

The land considered for plantations is generally considered poor agricultural land. The potential of a plantation site is characterized by an average weighted productivity index (AWPI) thus:

$$(AWPI) = \frac{\sum (LA)_i (PI)_i}{\sum (LA)_i} \quad (B-1)$$

where $(LA)_i$ is the land area (acres) of land of class i as defined by the Soil Conservation Service and $(PI)_i$ is the productivity index as defined in Reference 63. Although the productivity indices used above were defined on the basis of agricultural crops, it has been shown that a similar scale can be defined for forest-type crops.⁶⁴ In the present study, we assumed that the plantation was equally divided between land classes 4 and 6.

Site Characterization

The sites of the plantations are characterized by:

1. The average size of the parcels making up the plantation;
2. Distribution of the parcels within the geographic area containing the plantation (referred to as plantation density); and
3. Cultivation schedule required in the plantation.

In the present study, we assumed that the plantations were made of individual square parcels of 100 acres each distributed at random within a

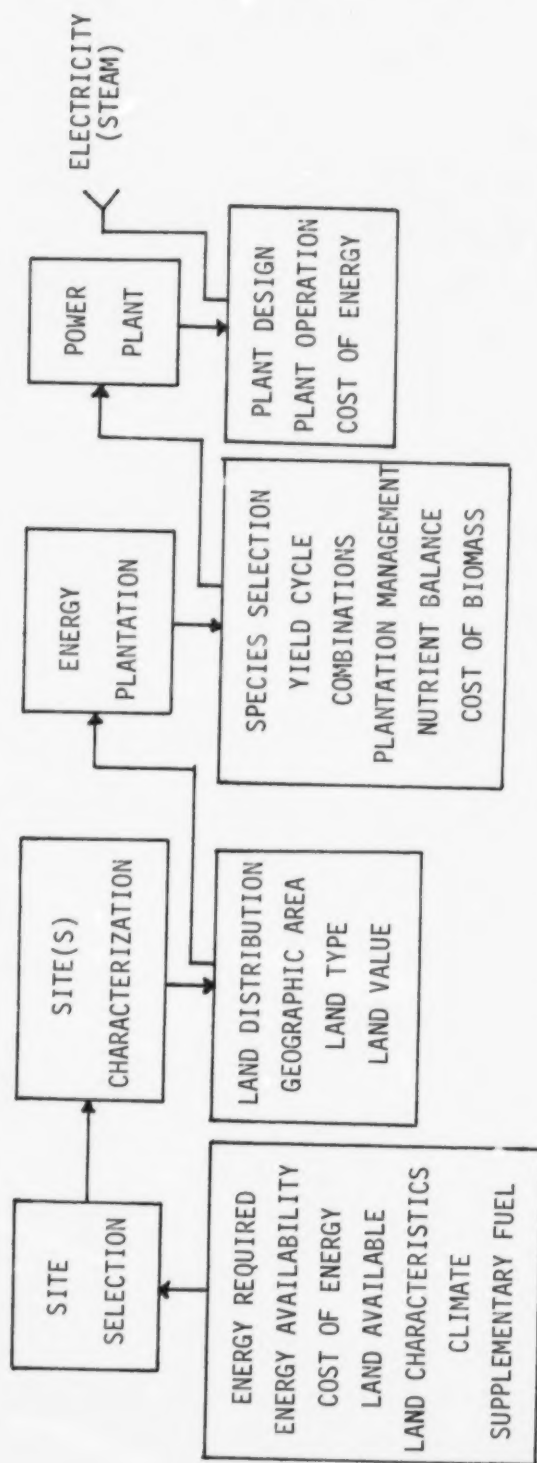


Figure B-1. Analysis procedure for potential Energy Plantation™ sites.

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certain geographic area. As discussed in Appendix A, the parcels making up the plantation are assumed to represent 15% of the geographic area of the plantation. The cultivation schedule required (whose purpose is mostly to control parasitic growth of weeds) is determined for each climatic region on the basis of the length of the growing season. The physical layout of the plantation is illustrated in Figure B-2.

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Energy Plantation™ Computer Model

The main functions of subroutines included in the Energy Plantation™ model are discussed in the following subsection.

Species Selection--

Based on data characterizing a given site, this subroutine selects candidate species for plantation application at this site from the species data bank. In the present case, hybrid poplar NE 388 was chosen for all climatic regions of interest.

Yield-cycle Combinations--

For each species retained in the selection process, this subroutine selects the most promising yield-cycle combinations on the basis of the highest yields predicted. Such a combination is characterized by a given planting density (ft^2 per tree at planting), age at first harvest, interval between coppice harvests, number of coppice harvests, and corresponding annual sustained yield (oven-dry tons/acre-year). The subroutine uses the plant growth model developed by ITC/Solar. This model takes into account survival and rate of growth as a function of age and planting density. The model predicts annual sustained yields within 3% to 10% of actual experimental data.⁴⁷ Experiments on abandoned farmland in Pennsylvania have shown that productivities of about 8 oven-dry tons/acre-year can be obtained with the hybrid retained in the present analysis. The yield-cycle considered here is 8 oven-dry tons/acre-year, 12 ft^2 /plant (about 3,600 plants/acre), and harvests every 3 years. This planting density was selected because it permits passage of machinery between the rows of plants to apply the sludge on a yearly basis.

Plantation Management--

For each yield-cycle combination retained, this subroutine determines the basic plantation design and management required. The plantation is assumed to be a self-contained operation. This subroutine analyzes the following functions:

- Plantation Management. A harvesting and planting schedule is determined to ensure sustained, essentially perpetual operation of the plantation. The plantation is divided into a number of equal planting units that are harvested according to the yield-cycle combinations determined earlier.

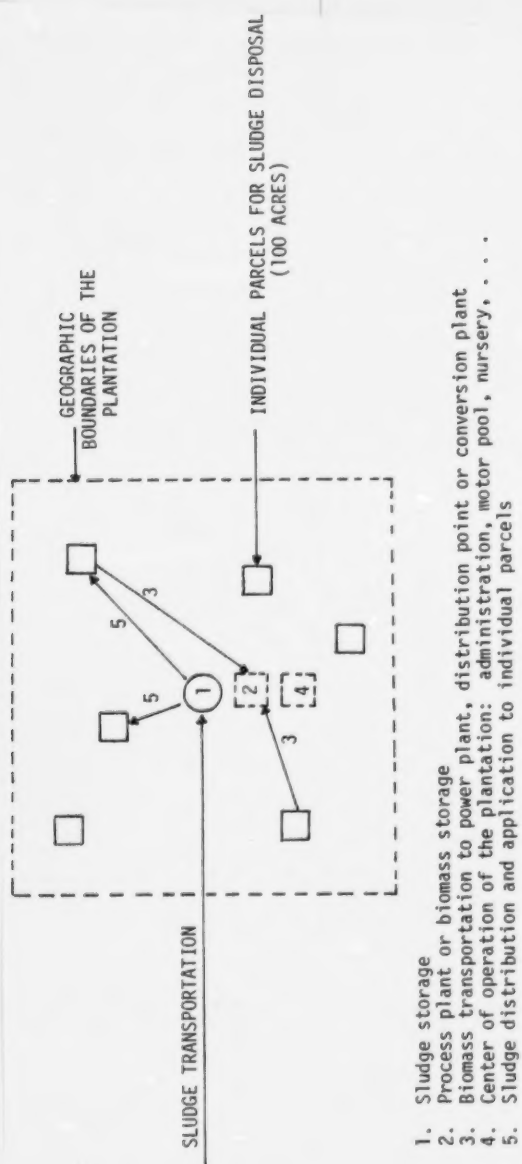
Each year, one planting unit is destroyed and replanted to ensure rejuvenation of the plantation and thus perpetual operation. The situation is illustrated in Figure B-3.

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1. Sludge storage
2. Process plant or biomass storage
3. Biomass transportation to power plant, distribution point or conversion plant
4. Center of operation of the plantation: administration, motor pool, nursery, . . .
5. Sludge distribution and application to individual parcels

Figure B-2. Typical operational layout of our energy plantation using sludge as fertilizer for sludge disposal.

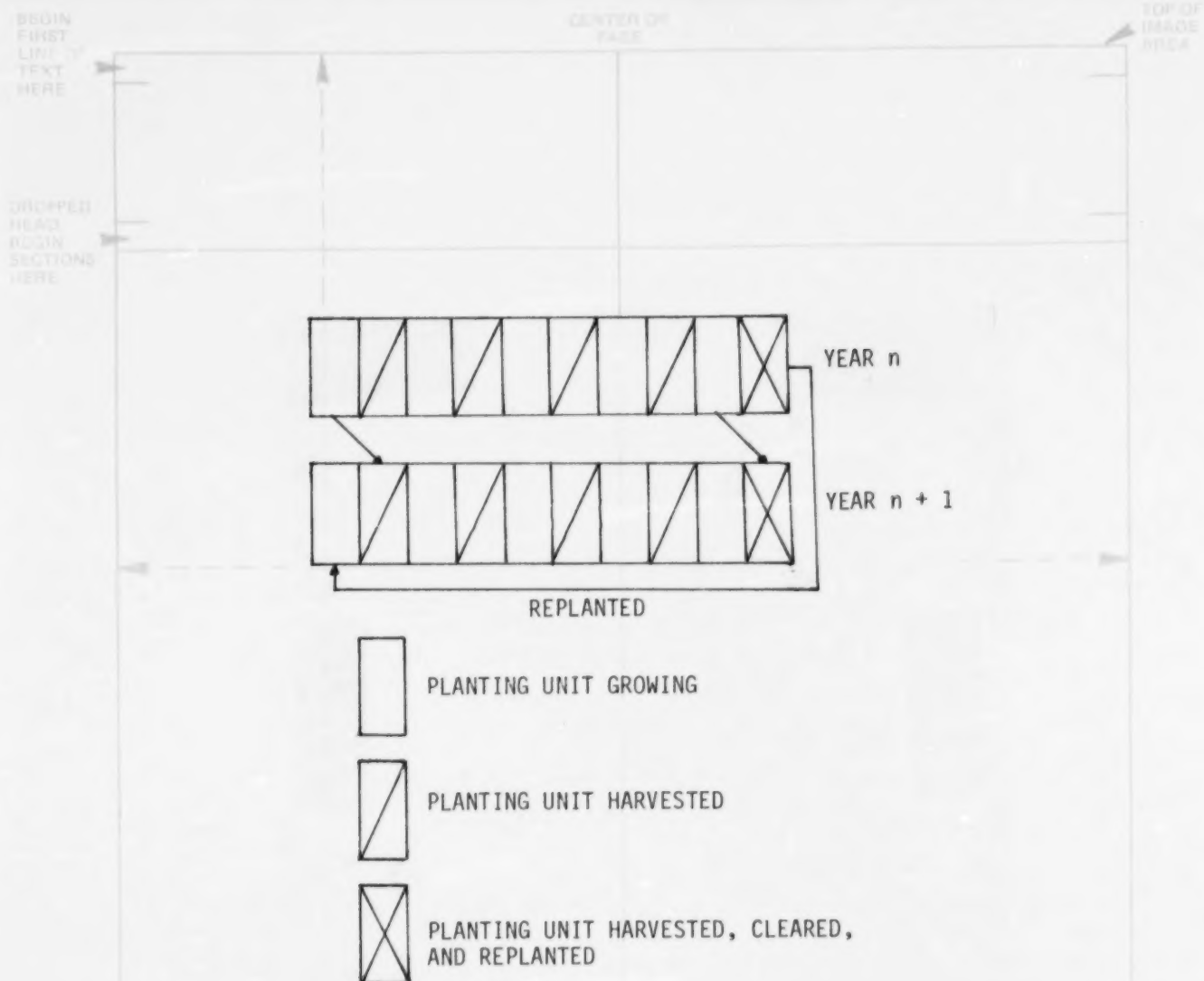


Figure B-3. Plantation operation schedule (hypothetical case of harvests every 2 years and five consecutive harvests from each plot before replanting).

- **Field Operations.** These operations include harvesting, biomass collection and transportation to the point of use, cultivation, fertilization, fungicide application, land-clearing and maintenance, clone material collection, replanting, and ash return and spreading on the land. Harvesting is assumed to be performed by machines similar to corn-forage harvesters. Such equipment is not produced at present, but it has been shown to perform satisfactorily on an experimental basis.⁶⁵ The wood chips produced by the harvester are collected in the field by dump wagons and stored temporarily at various field locations. From these, the chips are transported to the point of use by tractor trailers. Other operations are standard agricultural operations. In its evaluation of the equipment required, the computer program takes into account climatic conditions, the length of the growing season, and other factors that may influence the scheduling and thus the inventory of the equipment needed for the various field operations.
- **Nursery Operations.** Included are the production and storage of clones for the yearly replanting of a plantation unit. The clones required to replant are generated from the material harvested yearly, thus ensuring the maintenance of the genetic quality of the planting stock. The program takes into account differences in clone sizes suggested for good survival for the various species considered for the plantation.
- **Motor Pool Operations.** The main function of this operation is to maintain and repair the equipment, ensure fuel supplies, and supply the replacement equipment when justified.
- **Supervision.** This function includes supervision, dispatching, horticulturist support, and administration.
- **Plantation Installation and Start-up.** This phase includes all the operations required to bring the plantation to its full operational state (initial land-clearing, cultivation, planting, etc.). The product of this subroutine is a list of the equipment inventory and manpower required to establish and operate an Energy PlantationTM under the conditions specified previously - site, species, yield-cycle combination.

Nutrient Balance--

To ensure sustained biomass yields, nutrients removed from the land must be replaced through multiple and short-rotation harvests. A subroutine evaluates the amounts of nutrients (N, P, K, Ca) required. It takes into account the nutrients returned to the land through recycling of the ash from the boiler (80% of the ash is assumed to be returned to supply some of the P, K, and Ca needed), and it also considers the length of time between harvests. This latter parameter has a multiple effect, as it is assumed that nutrients are applied once at the beginning of each growing cycle. Some applied nutrients are lost through groundwater leaching or microbial decomposition, and some nutrients are returned through decomposition of fallen leaves.

These various effects are accounted for.⁶⁴ In the present study, most of the nutrients are supplied by the sludge.

Cost of Biomass--

The final phase of the Energy PlantationTM model is the calculation of (a) the cost of biomass delivered at the point of use (\$/oven-dry ton, \$/green ton, or \$/million Btu) for the various species and (b) corresponding yield-cycle combinations retained for analysis at a site. The cost is estimated either with the utility method of financing (debt is 65%, equity is 35%, and return on debt and equity are 11% and 9%, respectively) or with the municipal method of financing (6.375% on debt).

Cost estimates based on the plantation model just described were modified in the present case to include the costs for sludge storage, application to land (subsurface application), and costs for supplementary nutrients. Because the same equipment (tractor plus wagons) can deliver the harvested chips to a central point and distribute the sludge on its way back to the parcels, the application cost was taken as 15% of the cost given in Appendix A to account for the equipment modifications required for sludge application to the land.

Plantations smaller than about 4,200 ha (10,000 acres) cannot justify a full administration team, a motor pool with replacement equipment, and permanent field equipment (harvesters, etc.). In those cases, we assumed that all plantation operations would be subcontracted to local operators. Costs were estimated based on the operation hours determined by the computer program and hourly rates currently charged for the various field operations (data collected for farm operations in Northern Virginia).

Power Plant Subsystem

The fuel required by the boiler is supplied from the Energy PlantationTM. Dirt from the screener and ash are redistributed onto the Energy PlantationTM land so that their nutrient value is not lost. The electricity is the primary output of the power plant and is fed into a power grid for use as demanded by the specific site. Combustion air and tempering air for the chip dryer are supplied directly from the surrounding atmosphere.

The modeled power cycle is a conventional Rankine cycle used coal-fired and nuclear-fueled power plants. More exotic power cycles such as a gas turbine were not modeled, in keeping with the decision that the model should represent state-of-the-art equipment readily available for a demonstration system. The system components are similar to those that would appear in a simple coal-fired power plant with the addition of equipment to dry and screen the fuel before it enters the boiler. Storage space for dried fuel is provided in the event that a continuous supply of fuel from the Energy PlantationTM is interrupted.

The steam cycle in the power plant model is a simple cycle consisting of the four basic elements--boiler, turbine, condenser, and pump. To calculate the energy transfer rates to and from the steam in each of these components, certain relationships between various steam properties must be known.

These include, for example, the relationship between saturation temperature and pressure, the enthalpy of saturated liquid as a function of temperature, the entropy of saturated liquid as a function of temperature, the enthalpy of superheated steam as a function of temperature and pressure, and the entropy of superheated steam as a function of enthalpy and pressure. An algebraic expression for each of these relationships was found using least-squares curve-fitting techniques with steam table data.

In practice, additional components such as reheaters and feedwater extraction regenerative heaters are included in the steam cycle to increase its efficiency. The model can approximate the performance of an extraction steam cycle by including two factors in the model: (a) the ratio of Rankine cycle efficiency of the extraction cycle to the Rankine cycle efficiency of the simple cycle operating under the same conditions, and (b) the ratio of steam flow rate through the boiler to condensate flow rate through the condenser for the extraction cycle. Representative values of these factors were found as a function of turbine-inlet-steam pressure by analyzing the performance data from 10 coal-fired TVA power plants. From these data, the simple-cycle model could predict quite accurately the performance of extraction cycles using these factors as calculated from correlations with boiler pressure. With these correlations, accurate comparisons could be made of the performance and costs of large utility-sized coal-burning and wood-burning power plants.

A correlation for parasitic power for a wood-fired power plant was developed from a correlation for coal-fired plants given in the literature and from an analysis of the relative amounts of power used in the fuel-handling system and the rest of the plant. The parasitic power for a wood-fired plant was found to be twice that for the coal-fired plant. The correlation found is:

$$P_{\text{para}} = 9.2 \text{ MW } (P_g/100 \text{ MW})^{0.86} \text{ (wood-fired plant)} \quad (\text{B-2})$$

where P_{para} is parasitic power and P_g is gross electrical power output.

In a similar fashion, cost correlations for large wood-fired plants were developed from correlations for installation costs and operation and maintenance costs for coal plants available in the literature. The costs were divided into those for the fuel-handling system and those for the rest of the plant. The costs for a wood-fired power plant were found to be 20% higher than the costs for a coal-fired plant of the same size. On this basis, cost equations for large wood-fired power plants are as follows:

$$\text{Installation cost (1976 \$)} = 47.9 \times 10^6 + 468 P_g \text{ (KW)} \quad (\text{B-3})$$

$$\begin{aligned} \text{Operation and maintenance cost (1976 \$)} &= 1.96 \times 10^6 \\ &+ 2.66 P_g \text{ (KW)} \quad (\text{B-4}) \end{aligned}$$

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Installation costs for smaller wood-fired power plants were furnished by Mr. S. Hunter W. Brooks, a consulting engineer. Analysis of these cost data yielded the following correlation for smaller wood-fired plants:

$$\text{Installation cost (1976 \$)} = 18.7 \times 10^6 + 806 P_g \text{ (KW)} \quad (\text{B-5})$$

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Equations B-3 and B-5 for installation costs of wood-fired power plants yield the same cost at a power output of 86,400 kW. Hence, equation B-3 is used for installation costs of power plants producing 86,400 kW or more, and equation B-5 is used to calculate installation costs for power plants producing less than 86,400 kW. With the above equations as a basis, the model calculates the cost per unit of electricity by each of two financing methods-- the utility method and the municipal method.

The cycle considered represents current wood-burning boiler technology. It is a simple Rankine cycle with steam supplied at a pressure of 650 psia, a temperature of 399°C (750°F), and a turbine efficiency of 79%. A moisture content of 20% (wet basis) was specified for the fuel leaving the dryer, and an exhaust gas temperature of 93°C (200°F) was specified. The conditions of the combustion air supply were assumed to be 70% excess at a temperature of 22°C (70°F) and a relative humidity of 45% (specific humidity of 0.007).

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APPENDIX C

NUTRIENT AND WATER BALANCE FOR VARIOUS ENERGY CROPS

This appendix describes the methods used to determine the rate of sludge application on energy crops. The analysis is performed for the various climatic regions identified in Appendix A and for the various energy crops considered in those regions.

WATER BALANCE

Water availability during the growing season often limits biomass yields. Water requirements were estimated on the basis of local rainfall during the growing season,²⁹ plant requirements (pounds of water per point of biomass produced), and local evapotranspiration.²⁷

Typical water requirements during the growing season for energy crops are:

- Fast-growing deciduous species: 300 lb water/dry lb biomass⁶⁶
- Economic tree species: 190 lb water/dry lb biomass⁶⁶

The economic tree species referred to above include beech, Douglas fir and spruce, and perhaps local brush or desert species such as chaparral. But few data are available concerning the transpiration economy of the brush or desert species.

In the case of fast-growing deciduous species, 64 to 84 cm (25 to 33 in.) of water is required during the growing season to maintain productivity levels of 8 to 10 oven-dry tons/acre-year--the typical productivity levels for short-rotation plantations (see Appendix B). The values quoted above include 20% loss of rainfall through runoff and other losses.

Table C-1 summarizes the results for the five climatic regions shown in Figure C-1. The results of Table C-1 thus indicate that some kind of irrigation will be needed in regions A and B to sustain significant yields of hardwoods in managed plantations.

Note, however, that unmanaged plots of chaparral growing in waste areas of southern California display growth rates of about 2 oven-dry tons/acre-year. The impact of sludge application on these plots is not known.⁵²

TABLE C-1

WATER BALANCE FOR WOODY ENERGY CROPS IN THE FIVE CLIMATIC REGIONS

Region (1)	Rainfall (in.) (2)	Evapotranspiration (in.) (3)	Irrigation Needed ⁽⁴⁾ (acre - in.)	
			Hardwoods (5)	Economic Species (5)
A	1 - 3	5 - 50	30	20
B	4 - 13	20 - 70	40	25
C	15 - 30	0	0	0
D	12 - 31	-20 - +30	0	0
E	3 - 20	-20 - +20	5	3

(1) See Figure C-1 for the definition of the climatic regions.

(2) Average rainfall during the growing season - from (29).

(3) From (27). A positive sign indicates potential evapotranspiration larger than mean annual justification and vice versa for the negative sign.

(4) Irrigation needed to compensate for lack of sufficient rainfall during the growing season.

(5) Yields from 8 to 10 oven-dry tons/acre per year.



- A-Mediterranean Climate-
Dry summer-mild, wet winter
- B-Arid climate-hot, dry
- C-Humid Subtropical-mild winter
 hot, wet summer (Wash., Ore.,
 area mild, moist summer)
- D-Humid Continental-short
winter, hot summer
- E-Humid Continental-long
winter, warm summer
- Source: Reference 27

Figure C-1. Definition of the climatic regions used in the analysis.

The various climatic regions of Figure C-1 do not define absolute geographic boundaries: Parts of Wyoming may be more similar in climate to Region D than to Region E, for example.²⁸

The range of values quoted in columns 2 and 3 of Table C-1 represent variations observed within the climatic regions considered. Similarly, the values quoted for irrigation are an order of magnitude that may vary within a given region.

The climatic regions are used to simplify the analysis and define conditions that are relatively similar within a region. But in view of the significant variations in yield that can be and are observed within the climatic regions used, a sensitivity analysis of the impact of plant yield on the economics of the sludge disposal method will be performed.

NUTRIENT BALANCE

The following analysis describes the procedure used to determine the sludge application rate for the case of woody species. A similar procedure is followed for other energy crops.

Nutrient Requirements

Under steady-state conditions, we assume that the nutrient amounts to be supplied to an energy plantation are equal to those removed through harvesting (fixed by the crop) adjusted for losses.

The nutrient requirements were determined based on the following assumptions:

- yearly application of sludge
- factor of 4/3 to account for initial losses (runoff, etc.)
- subsurface application of sludge
- 3-year rotations for the energy plantation
- productivities of 8 to 10 oven-dry tons/acre-year

The method for estimating nutrient requirements is described in reference 37. Analysis results are shown in Table C-2.

Nutrient Balance and Sludge Application Rate

The sludge application rates may be estimated to satisfy the nitrogen, phosphorus, or other nutrient requirements.

Application Rate to Satisfy Nitrogen Requirements--

Median sludge compositions are assumed in this analysis (see Appendix A). The method described by Lofty et al.³¹ or Knezek et al.⁵⁰ is used to

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TABLE C-2
ANNUAL NUTRIENT REQUIREMENTS FOR FAST-GROWING HARDWOOD SPECIES

Productivity o.d.t/ay	Nutrient Requirements-lb/acre per year*				
	<u>N</u>	<u>Ca</u>	<u>K</u>	<u>Mg</u>	<u>P</u>
8	114	145	76	15	12
10	142	181	95	18	15

* Multiply by 1.201 to obtain value in kg/ha-year.

determine the nitrogen available. Thus for liquid sludge:

Total nitrogen 4.2%

Inorganic nitrogen . . . 0.2%

Nitrogen available in sludge is thus

$$(\% \text{ inorganic N} \times 20) + (\% \text{ organic N} \times 3) = \text{lb N/dry ton sludge applied (C-1)}$$

$$0.2 \times 20 + 4 \times 3 = 16 \text{ lb N/dry ton sludge}$$

Residual nitrogen from previous yearly applications, for 4% organic nitrogen (see Reference 31) is as follows:

Sludge applied 1 year earlier: tons/acre x 4.8 lb N/ton sludge

Sludge applied 2 years earlier: tons/acre x 3.2 lb N/ton sludge

Sludge applied 3 years earlier: tons/acre x 1.6 lb N/ton sludge

Thus for a yearly application of 1 dry ton of sludge, the residual nitrogen available is

$$4.8 + 3.2 + 1.6 = 9.6 \text{ lb N/dry ton sludge applied yearly (C-2)}$$

Under steady-state conditions, the application rate R (dry tons/acre-year) is given by

$$\text{lb N required} = R \times \text{lb N available/dry ton sludge}$$

where N required is shown in Table C-2, R = yearly sludge application rate (dry tons/acre-year), and N available/dry ton sludge is the sum of (C-1) and (C-2).

Thus

$$114/142 = R (9.6 + 16)$$

or

$$R \approx 4.5 \text{ dry tons/acre}\cdot\text{year for a productivity of 8 oven-dry tons/acre}\cdot\text{year}$$
$$\approx 5.6 \text{ dry tons/acre}\cdot\text{year for a productivity of 10 oven-dry tons/acre}\cdot\text{year}$$

The nutrients applied at these rates are shown in Table C-3. If 100% of the N required from sludge is supplied, only potassium has to be added to satisfy the nutrient requirements of the plantation.

Application Rate Needed to Satisfy the Phosphorus Demand--

The application rate needed to satisfy the phosphorus demand, including a loss factor of 1.33, is about 0.20 to 0.25 dry ton sludge/acre·year. The amounts of nutrients applied under those conditions are shown in Table C-4.

Application Rate Needed to Satisfy the Calcium and Magnesium Demand--

The application rate in this case is about 1.5 to 1.9 dry tons sludge/acre·year. The amounts of nutrients added under those conditions are shown in Table C-4.

Economic Considerations

The data in Tables C-3 and C-4 show that sludge application at a rate satisfying the nitrogen requirements of the plantation requires the least supplementary nutrients. For present agricultural prices,⁶⁷ the cost of the supplementary nutrients required to sustain productivities of 8 oven-dry tons/acre·year of hardwoods are \$5, \$29, and \$20/acre·year for application rates satisfying the nitrogen, phosphorus and calcium, and magnesium requirements, respectively. Also, satisfying the nitrogen requirements lead to the highest rates of sludge application.

Impact of Sludge Storage on Application Rate

As indicated in Appendix A, climatic conditions require that sludge be stored in some areas of the country before it is applied to the land. Storage reduces the sludge nitrogen and phosphorus content and thus modifies the application rates of sludge to the crop.

This effect was accounted for by defining an average sludge composition and taking into account the relative amounts being stored before application and those being applied without storage. The equation used to determine the average percent of a given nutrient is:

$$\text{Average \%} = \frac{(\text{original \%})}{365} \left[\left(\frac{\text{Days without storage}}{\text{storage}} \right) + \left(\frac{\text{Days with storage}}{\text{storage}} \right) \times (\% \text{ reduction due to storage}) \right]$$

*Calculations in this section are performed in English units. To obtain kg/dry metric ton, multiply lb/dry ton by 0.500. To obtain metric tons/ha·year, multiply tons/acre·year by 1.21.

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TABLE C-3
AMOUNTS OF NUTRIENTS ADDED FOR RATES OF APPLICATION OF
SLUDGE SATISFYING THE NITROGEN REQUIREMENTS OF HARDWOODS

<u>Nutrient</u>	<u>Amount Applied</u> <u>Yearly</u>	<u>Percentage of</u> <u>Requirements</u>
	lb/acre·year ⁽¹⁾	%
P	(2)/(3) 270/336	2,250
Ca	441/549	300
K	27/34	36
Mg	45/56	300
N	114/142	100

(1) Multiply by 1.1201 to obtain value in kg/ha·year.

(2) 8 oven-dry tons/acre·year.

(3) 10 oven-dry tons/acre·year.

TABLE C-4
AMOUNTS OF NUTRIENTS ADDED FOR RATES OF APPLICATION OF SLUDGE SATISFYING
THE PHOSPHORUS OR CALCIUM AND MAGNESIUM REQUIREMENTS FOR HARDWOODS

Nutrient	PHOSPHORUS DEMAND		Percentage of Requirements %	CALCIUM-MAGNESIUM DEMAND	
	Amount Added Yearly lb/acre·year	(1)/(2) 12/15		Amount Added Yearly lb/acre·year	Percentage of Requirement %
P			100	(1)/(2) 90/112	750
Ca	20/24		14	145/181	100
K	1.2/1.5		1.6	1/12	12
Mg	2/2.5		13	15/18	100
N	5.1/6.3		4.5	38.47	33

(1) 8 oven-dry tons/acre·year.

(2) 10 oven-dry tons/acre·year.

where the original % is the percent of the nutrient in the sludge without storage.

Some uncertainty exists concerning the percent reduction of N and P as a result of storage. The following percent reductions were used: Total N, 34%; inorganic N, 50%; phosphorus, 16%.^{1,50} The procedure outlined earlier under subsection Nutrient Balance and Sludge Application Rate was used to determine the application rates with storage for the five climatic regions considered. The results are presented in Appendix A.

HEAVY METALS BALANCE

For agricultural sludge use, application rates of 2 lb Cd/acre should not be exceeded.^{31,50} For a median Cd content of 16 ppm (Appendix A), the tolerable sludge application rate is

$$\text{Rate} = \frac{2 \text{ lb Cd/acre}}{16 \times 0.002} = 62.5 \text{ dry tons/acre}$$

This rate far exceeds those proposed for hardwood plantations. For a given CEC, the maximum amount of sludge that can be applied to satisfy agricultural limitations is^{31,50}

$$\text{Maximum amount of Cd} = \frac{(\text{CEC})}{\text{ppm Cd} \times 0.002} \text{ (dry T sludge)}$$

Most of the regions of interest for hardwood crops have CEC's between 10 and 20 meq/100 g (see Appendix A). Thus the maximum amount of sludge applicable per acre ranges from about 300 to slightly more than 600 dry tons/acre. At the maximum rate of application considered for hardwoods--7 dry tons/acre-year (see Table A-20)--the lifetime of the plantation would be from 40 to 80 years before the agricultural standards are reached, should they be considered. Thus Cd does not create any serious problems for the hardwood energy crop ecosystem.

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APPENDIX D

SAMPLE ANALYSIS OF A SITE

This appendix gives an example of the site analysis procedure used to evaluate the potential for energy crop production from sludge. The procedure follows the general methodology described in Section 4.

SITE ANALYSIS

This section considers the hypothetical case of a city with a population of 1 million located in Region C.

Annual Sludge Production

$$(\text{SLU}) = 1,000,000 \times \frac{0.14 \text{ lb}}{\text{capita-day}} \times \frac{365 \text{ days}}{\text{year}} \times \frac{1}{2,000 \text{ lb/ton}} = 25,500 \text{ dry tons/year}$$

See Appendix A for per-capita rate of sludge production.

Credit for Eliminating the Standard Method of Sludge Disposal

Credits are given in Appendix A, Table A-7 and Figure A-2. If the present system consists of dewatering and incineration,

$$(\text{CRIN}) = \$50/\text{dry ton} \times 25,550 \text{ dry tons/year} = \$1,277,500/\text{year}$$

If the present system consists of dewatering and landfill,

$$(\text{CRLA}) = \$49/\text{dry ton} \times 25,500 \text{ dry tons/year} = \$1,251,950/\text{year}$$

Energy Crop

The energy crop selected was the hardwood energy plantation described in Appendix B.

Area of the plantation: (CRAR) = $\frac{25,550 \text{ dry tons/year}}{4.8 \text{ dry tons/acre-year}} = 5,323 \text{ acres}$

Application rates by regions are given in Appendix A. The application rate chosen here (i.e., 4.8 dry tons/acre-year) corresponds to a hardwood productivity of 8 oven-dry tons/acre-year in Region C.

Storage Capacity and Land Application Costs

These costs are included in the cost of chip production, as described below.

Cost of Energy Crop Production

(CROCO) = $\$9.65/\text{oven-dry ton} \times 5,323 \text{ acres} \times \frac{8 \text{ oven-dry tons}}{\text{acre-year}} = \$410,936/\text{year}$

(See Appendix A, Figure A-18 for cost of wood chip production.)

Conversion Costs

This analysis assumes the wood chips produced are to be used as fuel and no intermediate conversion is required:

(CONCO) = 0

Credit From Energy Crop Sales

(CRCRO) = $\frac{\$10/\text{ton green}}{0.6} \times 5,323 \text{ acres} \times 8 \text{ oven-dry tons/acre-year} = \$709,733/\text{year}$

See Appendix A, Table A-17 for the sales value of the energy crop. The factor 0.6 accounts for the moisture content (60%) of the hardwood chips. The above credit assumes that any transportation costs of the chips to the point of use are assumed by the buyer, as appears to be the case for the pulp industry.⁵⁵

Functional Dependence of the Sludge Transportation and Land Costs on Distance from the Municipality

These functional dependences are given in Figures A-3 to A-11 and A-15. The quantity of interest in the economic evaluation of the process is the minimum value of the sum of land and transportation costs (see Section 4, Equation 2). Table D-1 and Figure D-1 give the combined minimum values of land and sludge transportation cost as a function of population. The data

TABLE D-1
MINIMUM COMBINED COST FOR SLUDGE TRANSPORTATION AND LAND (REGION C)

Population	Minimum Distance (miles)	Method of Transportation	Distance for Minimum Cost (miles)	Minimum Combined Cost 10^6 \$/year
10,000	5	Truck	5	0.0201
25,000	5	Truck	5	0.0217
50,000	10	Truck	10	0.0409
100,000	20	Truck	20	0.150
200,000	20	Truck-Pipeline	20	0.259
350,000	20	Pipeline	20	0.301
700,000	25	Pipeline	25	0.464
2,000,000	30	Pipeline	50	1.072
4,000,000	30	Pipeline	100	2.839

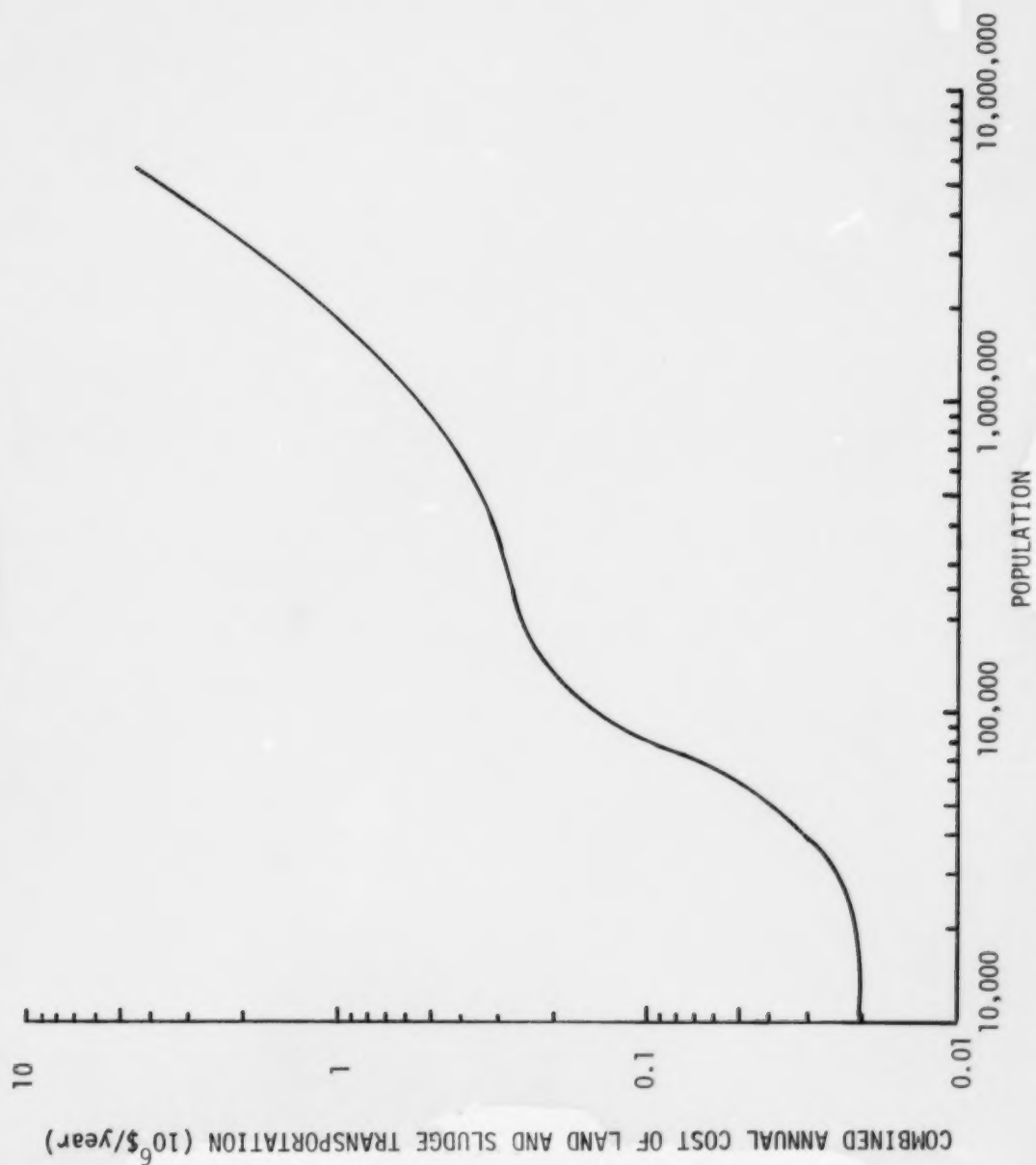


Figure D-1. Minimum annual combined cost for sludge transportation and land rental (Region C).

in Figure A-15 are used to determine the yearly land costs (interest on value: 6 3/8%, as for the plantation operations; see Appendix B). For each population size, the transportation method resulting in the minimum yearly transportation costs was assumed. The second column of Table D-1 shows the minimum distance that must be traveled from a municipality of a given population size to find land areas in which farmland represents about 90% of the land available. As discussed in Appendix A, the larger the city, the farther one must travel to find farmland.

The third column indicates the most economical method of liquid sludge transportation for each population size. These data are discussed in Appendix A, Figures A-3 to A-11. The fourth column indicates the distance from the city at which the combined sludge transportation and land costs reach the minimum value quoted in column five. For cities with populations up to and including about 700,000, the distances quoted in the second and fourth columns are equal. Thus as soon as a rural situation is reached (farmland equal to about 90% of the local land), the combined land and sludge transportation costs are at their minimum value. This situation results from the fact that the curve describing the functional dependence of land cost on distance is relatively flat (see Figure A-15), whereas the curves describing transportation costs versus distance are relatively steep. Thus increasing the distance from the city will decrease the land cost moderately, but it will increase the transportation costs sharply. For cities of 1 million or more, the cost of land decreases sharply as distance from the city increases (see Figure A-15). Then it becomes economically beneficial to travel further out of the city to reach areas of lower land costs, even if the process sludge transportation costs increase somewhat.

For the hypothetical case considered, the distance to be traveled to reach the minimum combined sludge transportation and land costs is about 50 miles, and the combined costs (TRACO) + (LANCO) amount to about \$550,000/year.

Economic Analysis

The economic analysis appears in Table D-2. The energy crop approach appears to be very attractive from an economic point of view. If the energy crop had to be transported back to the municipality for use in city services, for example, the transportation cost would be about

$$50 \text{ miles} \times \frac{\$0.10}{\text{ton-mile}} \times \frac{5,323 \text{ acres} \times 8 \text{ oven-dry tons/acre} \cdot \text{year}}{0.6} \approx \$348,200/\text{year}$$

Thus even with distribution of the biomass product, the approach is still economically feasible.

Table D-3 summarizes the results of the economic analysis for the five climatic regions considered and for cities ranging in population from 10,000 to 4 million.

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TABLE D-2
ECONOMIC ANALYSIS

<u>Item</u>	<u>Credits (\$/year)</u>	<u>Costs (\$/year)</u>
Incineration or Landfill	\$1,277,500	-
Biomass production	1,251,450	-
Transportation and land	-	\$411,000
Biomass value	-	550,000
Total credits:	<u>709,700</u>	<u>-</u>
Incineration	1,987,200	-
Landfill	1,961,650	-
Total cost for biomass:	-	961,000
Net credit:		
Incineration	1,206,200	
Landfill	1,000,650	

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TABLE D-3

ECONOMIC ANALYSIS OF THE PRODUCTION OF WOOD CHIPS FROM LAND USED FOR SLUDGE DISPOSAL
IN FIVE CLIMATIC REGIONS

	Climatic Region A									
	10,000	25,000	50,000	100,000	200,000	350,000	700,000	2,000,000	4,000,000	
Population										
Sludge DMT/y(1)	232	580	1,159	2,317	4,635	8,111	16,222	46,348	92,695	
(DST/y)(1)	(256)	(639)	(1,278)	(2,555)	(5,110)	(8,943)	(17,885)	(51,100)	(102,200)	
Incineration 10 ³ \$/y(2)	-	-	+102	+166	+296	+483	+930	+2,606	+5,110	
Landfill 10 ³ \$/y(3)	+61	+103	+153	+235	+373	+554	+930	+2,147	+4,088	
Area(4) hectares	37	92	185	369	739	1,293	2,585	7,386	14,772	
(acres)	(91)	(228)	(456)	(913)	(1,825)	(3,194)	(6,388)	(18,250)	(36,500)	
Biomass ODMT/y(5)	413	1,034	2,068	4,140	8,276	14,485	28,970	82,970	165,528	
(ODST/y)	(455)	(1,140)	(2,280)	(4,565)	(9,125)	(15,970)	(31,940)	(91,250)	(182,500)	
Production costs 10 ³ \$/y(6)	-18	-28	-40	-66	-116	-186	-345	-913	-1,752	
Biomass value 10 ³ \$/y(7)	+8	+19	+38	+76	+152	+266	+532	+1,520	+3,042	
Sludge transportation and land costs 10 ³ \$/y(8)	-21	-29	-59	-164	-318	-351	-609	-1,362	-3,809	
Distance(9) km	8	16	25	30	30	30	40	80	160	
(miles)	(5)	(10)	(15)	(20)	(20)	(20)	(25)	(50)	(100)	
Net dollar balance(10)	-	-	+41	+12	+14	+212	+508	+1,851	+2,591	
Incineration 10 ³ \$/y	+30	+65	+92	+81	+91	+283	+508	+1,442	+1,569	
Landfill 10 ³ \$/y	27	68	137	530	2,669	3,568	7,134	19,920	53,596	
Investment(11) 10 ³ \$										

See footnotes at end of table.

(continued)

TABLE D-3 (continued)

	Climatic Region B										
	10,000	25,000	50,000	100,000	200,000	350,000	700,000	2,000,000	4,000,000		
Population	232	580	1,159	2,317	4,635	8,111	16,222	46,348	92,695		
Sludge DMT/y(1)	(256)	(639)	(1,278)	(2,555)	(5,110)	(8,943)	(17,885)	(51,100)	(102,200)		
Incineration 10 ³ \$/y (2)	-	-	+102	+166	+296	+483	+930	+2,606	+5,110		
Landfill 10 ³ \$/y(3)	+61	+103	+153	+235	+373	+554	+930	+2,197	+4,088		
Area(4) hectares	30	76	152	304	608	1,064	2,129	+6,089	12,165		
(acres)	(75)	(188)	(376)	(751)	(1,503)	(2,630)	(5,260)	(15,029)	(30,059)		
Biomass ODMT/y(5)	340	853	1,705	3,406	6,816	11,927	23,854	68,157	136,318		
(ODMT/y)	(375)	(940)	(1,880)	(3,755)	(7,515)	(13,150)	(26,300)	(75,145)	(150,295)		
Production costs	-18	-30	-35	-58	-99	-158	-289	-777	-1,518		
10 ³ \$/y(6)	+6	+16	+31	+63	+125	+219	+439	+1,252	+2,505		
Biomass value 10 ³ \$/y(7)	-21	-29	-57	-158	-306	-330	-538	-1,239	-3,398		
Sludge transportation and land costs 10 ³ \$/y(8)	8	16	25	30	30	30	40	80	160		
Distance(9) km	(5)	(10)	(15)	(20)	(20)	(20)	(25)	(50)	(100)		
(miles)											
Net dollar balance(10)	-	-	+41	+13	+16	+214	+542	+1,842	+2,699		
Incineration 10 ³ \$/y	+28	+60	+92	+82	+93	+285	+542	+1,433	+1,677		
Landfill 10 ³ \$/y	23	56	113	436	2,482	3,241	6,288	17,987	47,155		
Investment(11) 10 ³ \$											

See footnotes at end of table.

(continued)

TABLE D-3 (continued)

	Climatic Region C									
	10,000	25,000	50,000	100,000	200,000	350,000	700,000	2,000,000	4,000,000	
Population										
Sludge DMT/y(1)	232	580	1,159	2,317	4,635	8,111	16,222	46,348	92,695	
(DST/y)(1)	(256)	(639)	(1,278)	(2,555)	(5,110)	(8,943)	(17,885)	(51,100)	(102,200)	
Incineration 10 ³ \$/y(2)	-	-	+102	+166	+296	+483	+930	+2,606	+5,110	
Landfill 10 ³ \$/y(3)	+61	+103	+153	+235	+373	+554	+930	+2,197	+4,088	
Area (4) hectares	21	54	108	215	431	754	1,508	4,308	8,617	
(acres)	(53)	(133)	(266)	(532)	(1,065)	(1,863)	(3,726)	(10,646)	(21,292)	
Biomass ODMT/y(5)	386	966	1,931	3,862	7,725	13,518	27,036	77,246	154,492	
(ODST/y)	(426)	(1,065)	(2,129)	(4,258)	(8,517)	(14,904)	(29,808)	(85,167)	(170,333)	
Production costs										
10 ³ \$/y(6)	-19	-29	-40	-64	-106	-165	-298	-715	-1,363	
Biomass value 10 ³ \$/y(7)	+7	+18	+21	+71	+142	+248	+497	+1,419	+2,839	
Sludge transportation and										
land costs 10 ³ \$/y(8)	-20	-22	-41	-150	-259	-301	-464	-1,072	-2,839	
Distance(9) km	8	16	25	30	30	30	40	80	160	
(miles)	(5)	(10)	(15)	(20)	(20)	(20)	(25)	(50)	(100)	
Net dollar balance(10)										
Incineration 10 ³ \$/y	-	-	+42	+23	+73	+265	+665	+2,238	+3,747	
Landfill 10 ³ \$/y	+29	+70	+13	+92	+150	+336	+665	+1,829	+2,725	
Investment(11) 10 ³ \$	16	40	80	309	2,228	2,797	5,138	15,358	38,388	

See footnotes at end of table.

(continued)

TABLE D-3 (continued)

	Climatic Region D										
	10,000	25,000	50,000	100,000	200,000	350,000	700,000	2,000,000	4,000,000		
Population	232	580	1,159	2,317	4,635	8,111	16,222	46,348	92,695		
Sludge DMT/y(1)	(256)	(639)	(1,278)	(2,555)	(5,110)	(8,943)	(17,885)	(51,100)	(102,200)		
Incineration 10 ³ \$/y(2)	-	-	+102	+166	+296	+493	+930	+2,606	+5,110		
Landfill 10 ³ \$/y(3)	+61	+103	+153	+235	+373	+554	+930	+2,197	+4,088		
Area(4) hectares	19	47	94	188	376	658	1,316	3,760	7,520		
(acres)	(47)	(118)	(232)	(465)	(929)	(1,626)	(3,252)	(9,291)	(18,582)		
Biomass ODMT/y(5)	341	842	1,683	3,374	6,741	11,798	23,597	67,415	134,831		
(ODST/y)	(376)	(928)	(1,856)	(3,720)	(7,432)	(13,008)	(26,016)	(74,328)	(148,656)		
Production costs	-21	-30	-38	-59	-98	-150	-267	-505	-989		
10 ³ \$/y(6)	+6	+15	+31	+62	+124	+217	+434	+1,239	+2,378		
Biomass value 10 ³ \$/y(7)	-20	-27	-54	-147	-285	-293	-456	-1,020	-2,667		
Sludge transportation and	8	16	25	30	30	30	40	80	160		
land costs 10 ³ \$/y(8)	(5)	(10)	(15)	(20)	(20)	(20)	(25)	(50)	(100)		
Distance(9) km											
(miles)											
Net dollar balance(10)	-	-	+41	+22	+37	+267	+641	+2,320	+3,832		
Incineration 10 ³ \$/y	+26	+61	+92	+91	+114	+328	+641	+1,911	+2,810		
Landfill 10 ³ \$/y	14	35	70	270	2,149	2,659	4,782	14,545	35,678		
Investment (11) 10 ³ \$											

See footnotes at end of table.

(continued)

TABLE D-3 (continued)

	Climatic Region E									
	10,000	25,000	50,000	100,000	200,000	350,000	700,000	2,000,000	4,000,000	
Population	232	580	1,159	2,317	4,635	8,111	16,222	46,348	92,695	
Sludge DMT/y(1)	(256)	(639)	(1,278)	(2,555)	(5,110)	(8,943)	(17,885)	(51,100)	(102,200)	
Incineration 10 ³ \$/y(2)	-	-	+102	+166	+296	+493	+930	+2,606	+5,110	
Landfill 10 ³ \$/y(3)	+61	+103	+153	+235	+373	+544	+930	+2,197	+4,088	
Area(4) hectares	19	46	92	185	369	646	1,293	3,693	7,386	
(acres)	(46)	(114)	(228)	(456)	(913)	(1,597)	(3,194)	(9,125)	(18,250)	
Biomass ODMT/y(5)	334	827	1,654	3,311	6,621	11,588	23,174	66,211	132,422	
(ODST/y)	(368)	(912)	(1,824)	(3,650)	(7,300)	(12,776)	(25,550)	(73,000)	(146,000)	
Production costs	-20	-29	-38	-58	-97	-162	-268	-694	-1,358	
10 ³ \$/y(6)	+6	+15	+30	+61	+122	+213	+426	+1,217	+2,433	
Biomass value 10 ³ \$/y(7)	-20	-27	-54	-147	-284	-292	-448	-1,013	-2,645	
Sludge transportation and	8	16	25	30	30	30	40	80	160	
land costs 10 ³ \$/y(8)	(5)	(10)	(15)	(20)	(20)	(20)	(25)	(50)	(100)	
Distance(9) km										
(miles)										
Net dollar balance(10)	-	-	+40	+22	+37	+252	+640	+2,116	+3,540	
Incineration 10 ³ \$/y	+27	+62	+91	+91	+114	+313	+640	+1,707	+2,518	
Landfill 10 ³ \$/y	14	34	68	264	2,140	2,642	4,739	14,445	35,346	
Investment(11) 10 ³ \$										

See footnotes at end of table.

(continued)

- +: Credit to the sludge disposal operation; -: Cost to the sludge disposal operation.
- (1) DMT/y: Dry metric tons/year; DST/y: Dry short tons/year.
 - (2) Cost of incineration if it was the chosen method of sludge disposal. This operation being eliminated in the energy crop approach, the associated costs are a credit to the sludge disposal operation.
 - (3) Cost of landfill if it was the chosen method of sludge disposal. This operation being eliminated in the energy crop approach, the associated costs are a credit to the sludge disposal operation.
 - (4) Plantation area required to dispose of the sludge at application rates satisfying the nitrogen requirements for a productivity of 17.9 oven-dry metric tons/hectare-year (8 oven-dry short tons/acre-year) of deciduous trees.
 - (5) ODMT/y: Oven-dry metric ton of biomass per year; ODST/y: Oven-dry short ton of biomass per year.
 - (6) Production costs of biomass including storage of sludge if needed, field operations, land preparation, transportation within the plantation but excluding land costs.
 - (7) Market value of the biomass produced in the plantation (see Table 18).
 - (8) Annual costs of land (6.375% of land value) and of sludge transportation for the distance corresponding to the minimum land and sludge transportation costs.
 - (9) Optimum distance from the city limits for which the sum of sludge transportation and land costs are minimum and equal to the value quoted under 8.
 - (10) Sum of items (2) or (3), (6), (7) and (8). A plus sign indicates that the sludge disposal through energy crop production rather than incineration or landfill disposal results in a credit of the amount indicated to the municipality (or a reduction of the cost of sludge disposal by the amount indicated).
 - (11) Up to a population of 100,000, the investment is the cost of the land; all plantation operations and sludge transportation are subcontracted. With population of 200,000 to 700,000, the investment includes land and pipeline costs, and the other operations are subcontracted. For populations of 2 million or more, the investment includes the land, the pipeline, and the plantation machinery and building.

ENERGY BALANCE

An energy balance for the hypothetical case above was performed as follows (see Figure D-2):

Auxiliary Fuel for Incineration

Significant variations in the amounts of auxiliary fuel required per ton of dry solids incinerated are recorded. Values ranging from about 20 to 50 gal of No. 2 fuel oil/dry ton of solids (3.2 GJ to 8.1 GJ/dry metric ton, or 2.75×10^6 to 7×10^6 Btu/dry short ton) are reported.^{7,12,56,57}

The auxiliary fuel required for a city of 1 million amounts to about 7.4×10^4 to 19×10^4 GJ/year (70 to 180×10^9 Btu/year). Co-incineration of solid wastes and sludge requires only about 2 gal of auxiliary fuel/dry ton of sludge.⁵⁶ Under those circumstances, the auxiliary fuel required would amount to about 7.4×10^3 GJ/year (7×10^9 Btu/year). It should be stressed that in nearly all cases, the auxiliary fuels used are either natural gas or oil derivatives.

Energy for Dewatering

The energy requirements quoted for dewatering vary from about 30 to 150 kWh/dry short ton.^{58,59,60} The data could not be used to establish a correlation between energy consumption and the size of the plants or the technique involved (vacuum filtration, pressure filtration, or continuous centrifuge). A value of 100 kWh/dry short ton was used (341,300 Btu electric/dry short ton or 1.03×10^6 Btu of fossil or nuclear fuel/dry short ton for a power plant with an overall efficiency of 33%). In the case considered, the dewatering operation thus requires about 2.6×10^6 kWh/year, or about 8.17 GJ/year (7.74×10^6 Btu) of fossil fuels.

Dewatered Sludge Transportation

Truck transportation of dewatered sludge to a landfill located 20 miles from the wastewater treatment plant will require about 2.07×10^{10} Btu/year.²²

Sludge Transportation to Plantation

The 5% solid sludge is transported from the treatment plant to the plantation by means of a 50-mile pipeline (10-in. diameter). The energy required was estimated to be 176,180 kWh/year (see reference 22), or 0.6×10^9 Btu electricity/year, or 1.92×10^3 GJ (1.82×10^9 Btu) of fossil fuel for a 33% efficient electric power plant.

Energy Requirements for the Energy Crop Plantation

The Energy Plantation computer program described in Appendix B estimates the amounts of diesel and gasoline fuels required for the field operations and transportation within the plantation area. In the case considered (5,323-acre plantation), these amount to about 6.9×10^3 GJ/year (6.5×10^9 Btu/year).

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Energy Content of the Energy Crop

The energy content of the energy crop (wood chips) amounts to:

$$5,323 \text{ acres} \times \frac{8 \text{ oven dry tons}}{\text{acre-year}} \times 2,000 \frac{\text{lb}}{\text{ton}} \times 8,600 \frac{\text{Btu}}{\text{lb}} = 7.32 \times 10^{11} \text{ Btu/year}$$

or $7.72 \times 10^5 \text{ GJ/year}$

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Transportation of the Energy Crop to the Point of Use

If the energy crop is not used within the plantation area, the wood chips produced will have to be delivered to their point of use. We assume that the chips will be transported to the city, 50 miles from the plantation, by long-haul tractor trailers (3 miles/gal diesel fuel, 30-short-ton capacity). The yearly energy input amounts to about $1.16 \times 10^4 \text{ GJ/year}$ ($1.1 \times 10^{10} \text{ Btu/year}$).

The overall energy balance for the case considered is shown in Figure D-2 and detailed in Table D-4.

As the table shows, if the energy crop replaces incineration, a net energy credit of about $8.4 \times 10^5 \text{ GJ/year}$ ($800 \times 10^9 \text{ Btu/year}$) is recorded, mostly as a result of the energy content of the energy crop. The total energy credit amounts to about 36 GJ/dry metric ton of sludge treated ($31 \times 10^6 \text{ Btu/dry short ton}$). Of the amount, about 3.5 GJ/dry metric ton ($3 \times 10^6 \text{ Btu/dry short ton}$) represent a saving of fossil fuels otherwise used, and 32.5 GJ/dry metric ton ($28 \times 10^6 \text{ Btu/dry short ton}$) are generated through the energy crop. If the energy crop replaces landfilling of dewatered sludge, a net energy credit of $8 \times 10^5 \text{ GJ/year}$ ($760 \times 10^9 \text{ Btu/year}$) is recorded. This credit amounts to about 33.7 GJ/dry metric ton of sludge treated ($29 \times 10^6 \text{ Btu/dry short ton}$). The credit is created by a decrease in fossil fuel consumption of about 1.16 GJ/dry metric ton of sludge ($1 \times 10^6 \text{ Btu/dry short ton}$) and the generation of 32.6 GJ/dry metric ton of sludge ($28 \times 10^6 \text{ Btu/short ton}$) of biomass energy.

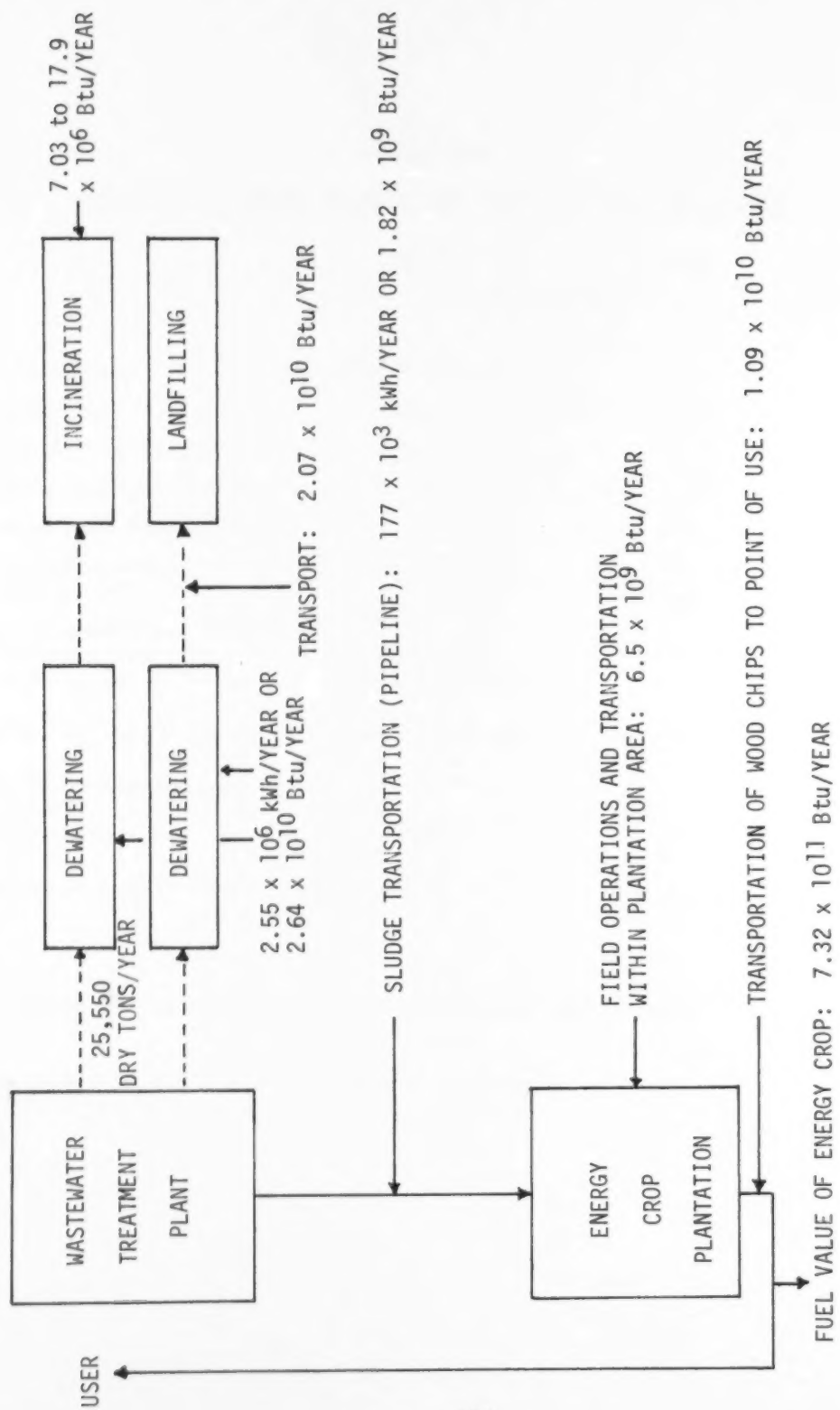


Figure D-2. Energy balance for a hypothetical site with a population of 1 million. (Energy crop: wood chips for fuel, Region C.)

TABLE D-4
COMPARATIVE ENERGY BALANCE FOR CITY OF 1 MILLION PEOPLE

	<u>Credit</u> 10 ⁹ Btu/year*	<u>Used</u>
Incineration	(7) ⁽¹⁾ -70-180	-
Dewatering	26.4	-
Transport to Landfill	20.7	-
Sludge Transportation	-	1.82
Energy Crop Production	-	6.5
Transportation of Energy Crop	-	10.9
Net if Dewatering and Incineration are Eliminated	(746) ⁽¹⁾ -809-919	-
Saving of Fossil Fuels:	(14) ⁽¹⁾ -77-187	-
Net if Dewatering and Landfill are Eliminated	760	-
Saving of Fossil Fuels:	27.9	-

(1) Value for coincineration of solid wastes and sludge.

* Multiply by 1.055×10^3 to obtain GJ/year.

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